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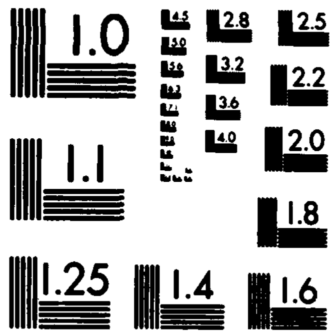

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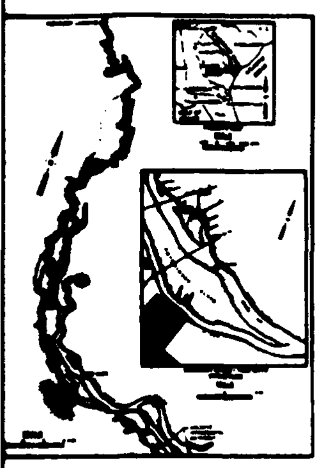
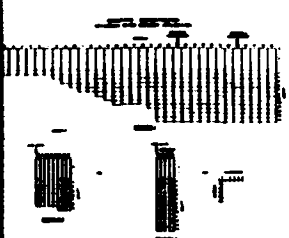
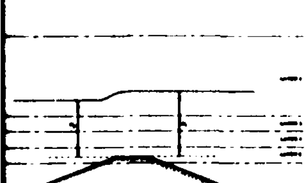
ENVIRONMENTAL IMPACT RESEARCH PROGRAM

TECHNICAL REPORT EL-87-4

APPLICATION OF CE-QUAL-W2 TO THE SAVANNAH RIVER ESTUARY







by

Ross W. Hall

Environmental Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631

June 1987

Final Report

Approved For Public Release, Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under EIRP Work Unit 31730

87 9 18 0?9

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188
Exp Date Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Technical Report EL-87-4	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION USAEWES Environmental Laboratory 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) PO Box 631 Vicksburg, MS 39180-0631	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION US Army Corps of Engineers 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20314-1000	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO / TASK NO / WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)
Application of CE-QUAL-W2 to the Savannah River Estuary

12. PERSONAL AUTHOR(S)
Hall, Ross W.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final report	FROM ____ TO ____	June 1987	85

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield VA 22161.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	CE-QUAL-W2 (computer program) Hydrodynamics (mathematical model) Savannah River Estuary Water quality (mathematical model)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report details the application of a two-dimensional, laterally averaged, water quality code, CE-QUAL-W2, to the Savannah River Estuary. Two levels of kinetic formulations were tested: (1) dissolved oxygen (DO) and biochemical oxygen demand (BOD); and (2) DO, BOD, nutrients, and algae. Experiments were conducted using the DO-BOD formulation to demonstrate the utility of CE-QUAL-W2 for investigating changes in upstream regulation and BOD loadings. Sensitivity analyses were conducted using both kinetic formulations in order to investigate the importance of tidal boundary constituent concentrations.

The numerical water quality code permitted the characterization of longitudinal and vertical gradients and demonstrated its usefulness for estuarine environmental assessment. The application revealed two critical problem areas: geometrical schematization and specification of external head boundary constituent profiles.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

PREFACE

This study was conducted by the Environmental Laboratory (EL) of the US Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss., under the Environmental Impact Research Program (EIRP) Work Unit 31730, "Environmental Impacts of Modifying Estuarine Circulation and Transport Processes." The EIRP is sponsored by the Office, Chief of Engineers (OCE), US Army, Washington, DC. Dr. John Bushman and Mr. Earl Eiker were OCE Technical Monitors, and Mr. Dave Mathis was Water Resources Support Center Technical Monitor. Dr. Roger T. Saucier was EIRP Program Manager.

This report details the application of a two-dimensional, laterally averaged, water quality code, CE-QUAL-W2, to the Savannah River Estuary, where resolution of both vertical and longitudinal gradients was desired. The report is intended for an audience that is familiar with numerical water quality modeling.

Mr. Ross W. Hall, Water Quality Modeling Group (WQMG), prepared the report under the supervision of Mr. Mark S. Dortch, Chief, WQMG; Mr. Donald L. Robey, Chief, Ecosystem Research and Simulation Division; and Dr. John Harrison, Chief, EL. This report was edited by Ms. Lee T. Byrne of the WES Information Products Division.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

This report should be cited as follows:

Hall, R. W. 1987. "Application of CE-QUAL-W2 to the Savannah River Estuary," Technical Report EL-87-4, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

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PART I. INTRODUCTION

General Comments

1. Coastal construction and operation activities at US Army Corps of Engineer (CE) water resource projects can impact the quality of surface estuarine waters. Numerical water quality models are required to assess these impacts, to evaluate various structural and operational alternatives for water quality control, and to determine cause and effect relationships of water quality problems. Frequently, the impacts are related to vertical stratification, such as bottom anoxia or transport of larvae and contaminants. Consideration of these impacts requires the use of numerical water quality models with resolution in both the vertical and longitudinal dimension.

2. This report describes the application of CE-QUAL-W2 to an estuarine system where vertical and longitudinal resolution was required. CE-QUAL-W2 is a two-dimensional, laterally averaged, water quality model that was developed to assist in the analysis of water quality problems in estuaries and reservoirs where buoyancy is important and where lateral homogeneity can be assumed. Detailed description and user guidance are provided in the report "CE-QUAL-W2: A Numerical Two-Dimensional, Laterally Averaged Model of Hydrodynamics and Water Quality; User's Manual" (Environmental and Hydraulics Laboratories 1986).

3. This application consisted of two levels of constituent kinetic formulations: (a) dissolved oxygen (DO) and biochemical oxygen demand (BOD) and (b) DO, BOD, nutrients, and algae. Sensitivity analyses were conducted using both levels of constituent kinetic formulations. Tidal boundary DO and BOD concentrations were varied in the DO-BOD formulation, and the system tidally averaged DO was noted as the response variable. Tidal boundary algal concentration and maximum algal growth rate were varied in the second formulation with system tidally averaged algal concentration noted as the response variable. The purpose of the sensitivity experiments was to investigate the importance of tidal boundary constituent concentrations. Experiments were conducted using the DO-BOD formulation to demonstrate the utility of CE-QUAL-W2 for investigating changes in upstream regulation and BOD loadings.

Study Area

4. The Savannah River basin is located in southwestern North Carolina, western South Carolina, and northern Georgia. The confluence of the Tugaloo and Seneca rivers at Hartwell, Ga., form the Savannah River, which flows along the Georgia-South Carolina state line to the Atlantic Ocean. Stream discharges in the basin are typically high in the winter and early spring, decrease during the summer, and remain low during the autumn. Freshwater flow is regulated through upstream reservoirs.

5. The Savannah River is tidal for approximately 70 km, from its mouth to near Ebenezer Landing (River Mile (RM) 44.7). A deep-draft harbor is maintained at Savannah, Ga. The channel of the Savannah Harbor is maintained from the Atlantic Ocean upestuary to RM 21.3. The tidal variation of the Savannah River Estuary of over 2 m is exceeded along the east coast only by the estuarine waters of Maine.

6. A unique feature of the harbor designed to exploit the large tidal variation is a sediment basin and tide gate to reduce sedimentation within the Savannah Harbor (Figure 1). The sediment basin tide gate plan consists of a dredged sediment basin at the lower end of Back River, construction of a tide gate in Back River, and various dredging and channel improvements. The tide gate is controlled to open during the flood portion of the tidal cycle and then to close at high-water slack. The tidal prism in the Back and Middle rivers augment ebb flow through the Front River. The higher resulting ebb velocities in Front River tend to move sediment past the Savannah Harbor and concentrate much of the shoaling in the sediment basin.

Objectives

7. The primary objective of the Environmental Impact Research Program (EIRP) work unit entitled "Environmental Impacts of Modifying Estuarine Circulation and Transport Processes" was the development of a CE estuarine water quality modeling capability that could relate changes in water quality to physical changes, such as circulation. Capability development included the selection and refinement of numerical water quality codes. The numerical water quality model CE-QUAL-W2 was selected for estuaries where vertical and

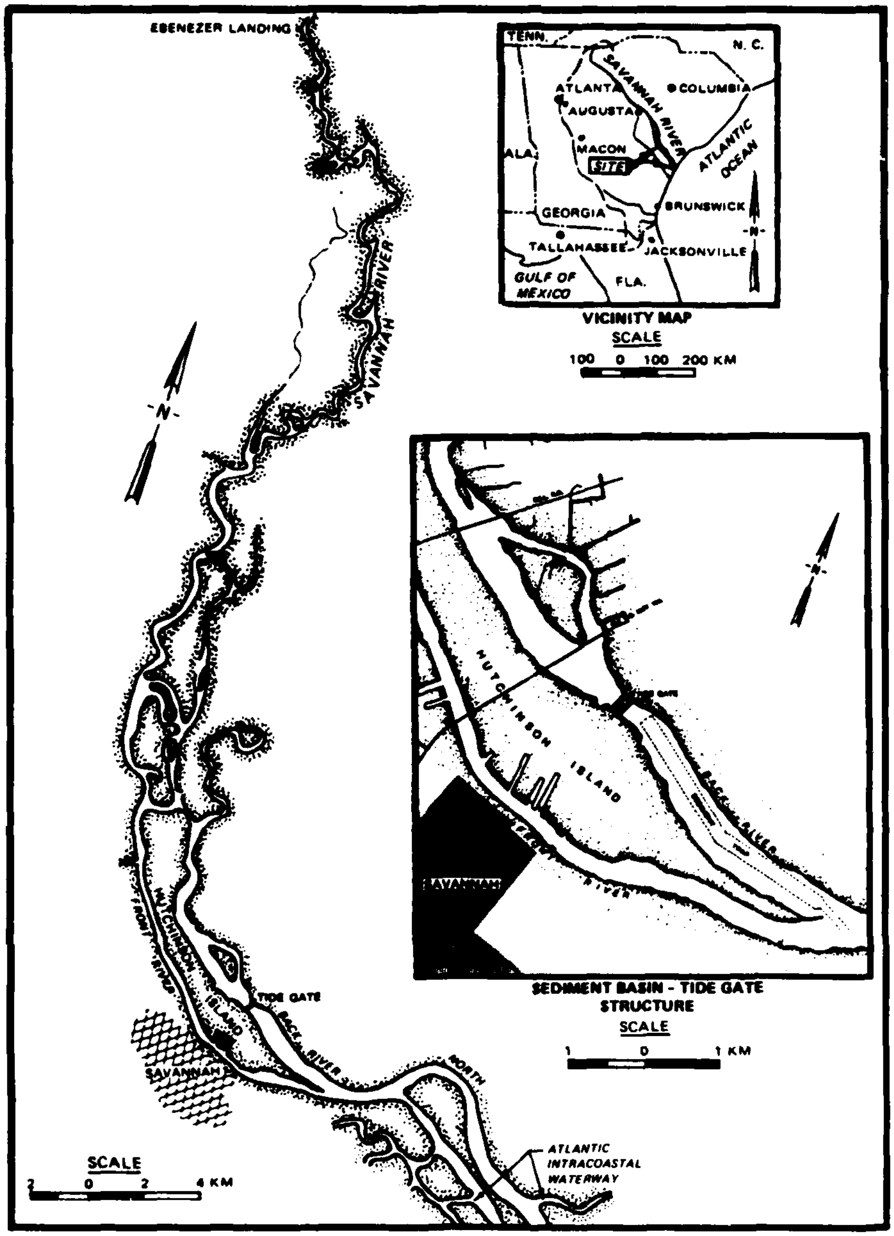

Figure 1. Study area and sediment basin-tide gate structure

longitudinal resolution was required and where lateral homogeneity could be assumed.

8. The Savannah River Estuary was selected for the test application because of the availability of data and information from previous modeling studies. The US Army Engineer Waterways Experiment Station (WES) coordinated a comprehensive water quality survey of the Savannah River Estuary during the

autumn of 1979 and late summer of 1980 (Pennington and Bond 1981; Shingler et al. 1981). This survey was conducted to assist the US Army Engineer District, Savannah (SAS), in the preparation of a plan of study that resulted in the application of the one-dimensional water quality numerical code by Lawler, Matusky, and Skelly Engineers (LMS) (1983) to investigate the DO resources of the Savannah River Estuary. In addition to the availability of data, the Savannah River Estuary is deep and narrow so that the lateral homogeneity assumption was valid.

9. Additional objectives of the present study included the identification of minimum data requirements and recommended sampling designs for estuarine application and the identification and formulation of procedures for data summarization and preparation for model application.

10. This report provides the results of the application of CE-QUAL-W2 to the Savannah River Estuary for the period August 1980. Part II of this report describes the application procedure, Part III presents the study results, and Part IV presents the study conclusions.

Water Quality Data Resources

11. The survey results (Pennington and Bond 1981; Shingler et al. 1981) and the effluent data reported in LMS (1983) were used in this study. Table 1 summarizes the survey data used for the Savannah River application, as follows:

- a. The center-line survey was conducted weekly during August 1980 at 16 stations along the main channel of the estuary and provided water quality constituent profiles used for model adjustment.
- b. The 13-hr survey was conducted four times at weekly intervals at the downstream study boundary. Each weekly study consisted of water quality constituent profiles collected hourly over a 13-hr period. The results of the 13-hr survey were used to specify tidal conditions.
- c. The diel study was conducted weekly at the upstream boundary of the study area. Surface to bottom profiles were taken every 4 hr for measurements of temperature, DO, and conductivity. The results of the diel study were used to specify freshwater flow boundary conditions.

Table 1

Survey Data Used for the Savannah River Estuary Application

Survey Name	Sampling Dates 1980	Stations Total No.	Stations Extent (RM)*	Sampling Positions	Sampling Frequency per Survey	Constituents Monitored
			Water Quality Survey			
Center line	5, 12, 20, 27 Aug	10	5.9–21.5	Right channel prism w 1-m depth intervals	Once	Temp, DO, conductivity
				Right channel prism surface, bottom, and 2 intermediate depths	Once	BOD_5, NH_4, NO_2+NO_3, P
		6	25.0–44.7	Midchannel w 1-m depth intervals	Once	Temp, DO, conductivity
				Midchannel surface and bottom	Once	BOD_5, NH_4, NO_2+NO_3, P
13-hr	6, 13, 19, 26 Aug	1	5.9	Right channel prism w 1-m depth intervals	Every hr for 13 hr	Temp, DO, conductivity
				Right channel prism surface, bottom, and 2 intermediate depths	Every hr for 13 hr	BOD_5, NH_4, NO_2+NO_3, P
Diel	7–8, 12–13, 19–80, 26–27 Aug	1	44.7	Midchannel w 1-m depth intervals	Every 4 hr for 24 hr	Temp, DO, conductivity
Productivity	6, 13, 19, 26 Aug	1	5.9	Right channel w 80, 50, 20, 1, 0% sunlight penetration	Once	Initial, light, and dark bottle DO
Sediment oxygen demand	1–5 Oct	3	5.9, 16.3, 21.5	Bottom	4 or 5 replicates	Oxygen uptake rate
			Hydrodynamic Survey			
30-day	24 Jul–27 Aug	2	5.9, 11.0	Right channel	6 min	Water surface elevation
13-hr	14 Aug	4	5.9, 11.4, 17.2	Left and right channel prism surface, middepth, bottom	hourly	Water depth, current speed and direction, salinity
			44.7	Midchannel surface, middepth, bottom		

* RM = River Mile.

d. Experiments to estimate production by the light-dark bottle method were conducted weekly at the downstream boundary concomitant with the 13-hr survey. The results of the productivity survey were used to estimate the light attenuation coefficient and the fraction of incident solar radiation absorbed at the water surface.

e. Sediment oxygen demand rates were determined at three locations along the lower reach of the study area. The results were extrapolated to assign sediment oxygen demand rates to the entire study area.

f. The 30-day hydrodynamic survey provided water surface level records that were used to specify the tidal boundary elevation and were also used for model adjustment.

g. The 13-hr hydrodynamic study consisted of tidal velocity measurements taken at 1-hr intervals at the upstream, downstream, and two intermediate locations on 14 August 1980. The results were used for model adjustment.

PART II. APPLICATION PROCEDURE

Geometric Schematization

12. The modeled study area extended from the confluence of the Atlantic Intracoastal Waterway (RM 5.9) to Ebenezer Landing (RM 44.7) and included the reentrant Back River connected with the main branch at RM 10.6 and RM 19.8 (Figure 1).

13. The Savannah River Estuary is represented in the model as three branches: Branch 1 was the main channel between RM 5.9 and RM 44.7; Branch 2 was the upstream section of Back River from the tide gate to its intersection with the main channel at RM 19.8; and Branch 3 was the downstream section of Back River from the tide gate to its intersection with the main channel at RM 10.6. The tide gate operation was represented as withdrawals from Branch 3 during flood tides with insertion of the withdrawals as flows into Branch 2.

14. Branch 1 Δx was 2 km, and, the Δx for Branches 2 and 3 was 1 km, where Δx is the cell length. Branch 1 Δx of 2 km was a balance between sufficient refinement to characterize phenomena of interest (effluent discharges, branch intersections, and prototype data sampling stations) and unnecessary computational costs. The selection of Δx of 1 km for Branches 2 and 3 was mandated by the requirement for a minimum of three computational segments per layer. The plan view segmentation with segment numbering is displayed in Figure 2. The main channel consisted of Segments 2 through 33; the upstream section of Back River consisted of Segments 36 through 43; and the downstream section of Back River consisted of Segments 46 through 49.

15. One study objective was to characterize the vertical distribution of water quality constituents. At 173-m^3/sec discharge of the Savannah River at New Savannah Bluff Dam, the surface elevation at Ebenezer Landing is 3.47 m. The surface elevation at the tidal boundary (RM 5.9) at mean low water (MLW) is -1.04 m. The resultant surface slope is 7.2×10^{-5} resulting in a total elevation difference of 4.5 m between the model boundaries. Initial simulations indicated that instantaneous water surface elevations extending over several model layers resulted in numerical instabilities. Therefore, a surface layer thickness of 5 m was selected, with the remaining layers 1 m thick. The selection of varying layer thicknesses required modification of

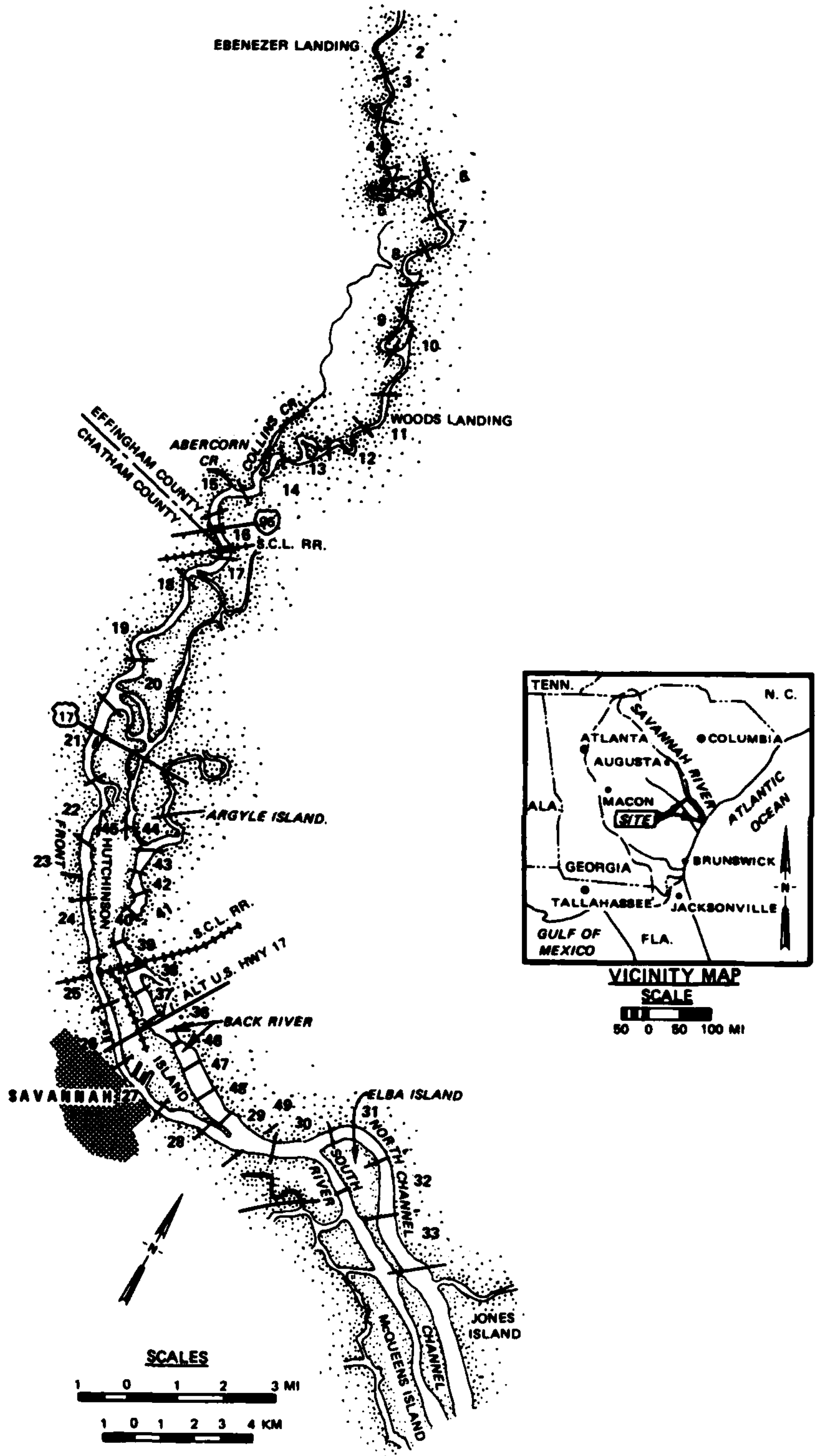

Figure 2. Plan view segmentation and segment numbering

the code. Figure 3 displays the vertical and longitudinal geometric schematization.

16. The procedure used to obtain cell widths involved the use of the Hydrologic Engineering Center code GEDA and the preprocessor GIN. GEDA uses cross-sectional data from ranges at irregular intervals and produces estuary widths as functions of elevation at regular intervals. GIN uses GEDA output as input and produces the geometry (BA) cards read by CE-QUAL-W2.

17. Estuary geometry data were abstracted from the following sources:

a. Natural Chart 11512, Savannah River and Wassaw Sound, National Oceanic and Atmospheric Administration (NOAA), 16 July 1977.

b. Nautical Chart 11514, Savannah River, Savannah to Brier Creek, South Carolina-Georgia, NOAA, 7 January 1978.

c. Annual Survey-1981, Savannah Harbor, Georgia, US Coastal Highway No. 17 to Sea, US Army Engineer District, Savannah.

d. Navigation Charts, Savannah River, Georgia and South Carolina, Savannah to Augusta, June 1980, US Army Engineer District, Savannah.

e. Design Memorandum 2, Sediment Basin, Savannah Harbor, Georgia, Tide Gate Structure, Vol I of II, US Army Engineer District, Savannah, 31 January 1969.

f. Design Memorandum 3, Sediment Basin, Savannah Harbor, Georgia, Fresh Water Control Plan and Appurtenances, US Army Engineer District, Savannah, 3 April 1970.

18. The geometry source publications related depths in feet to MLW or a low-water plane above Big Collins Creek corresponding to a discharge of 6,100 cfs (173 m^3/sec) at New Savannah Bluff Dam. The following values were used to relate depth to 0.0 ft* MLW:

RM	MSL,** ft
5.9	-3.4
7.7	-3.5
9.4	-3.6
10.9	-3.6
12.8	-3.6
14.4	-3.6
16.3	-3.6
18.0	-3.6
19.6	-3.6
21.5	-3.5

* To convert feet into metres, multiply by 0.3048.

** MSL = mean sea level.

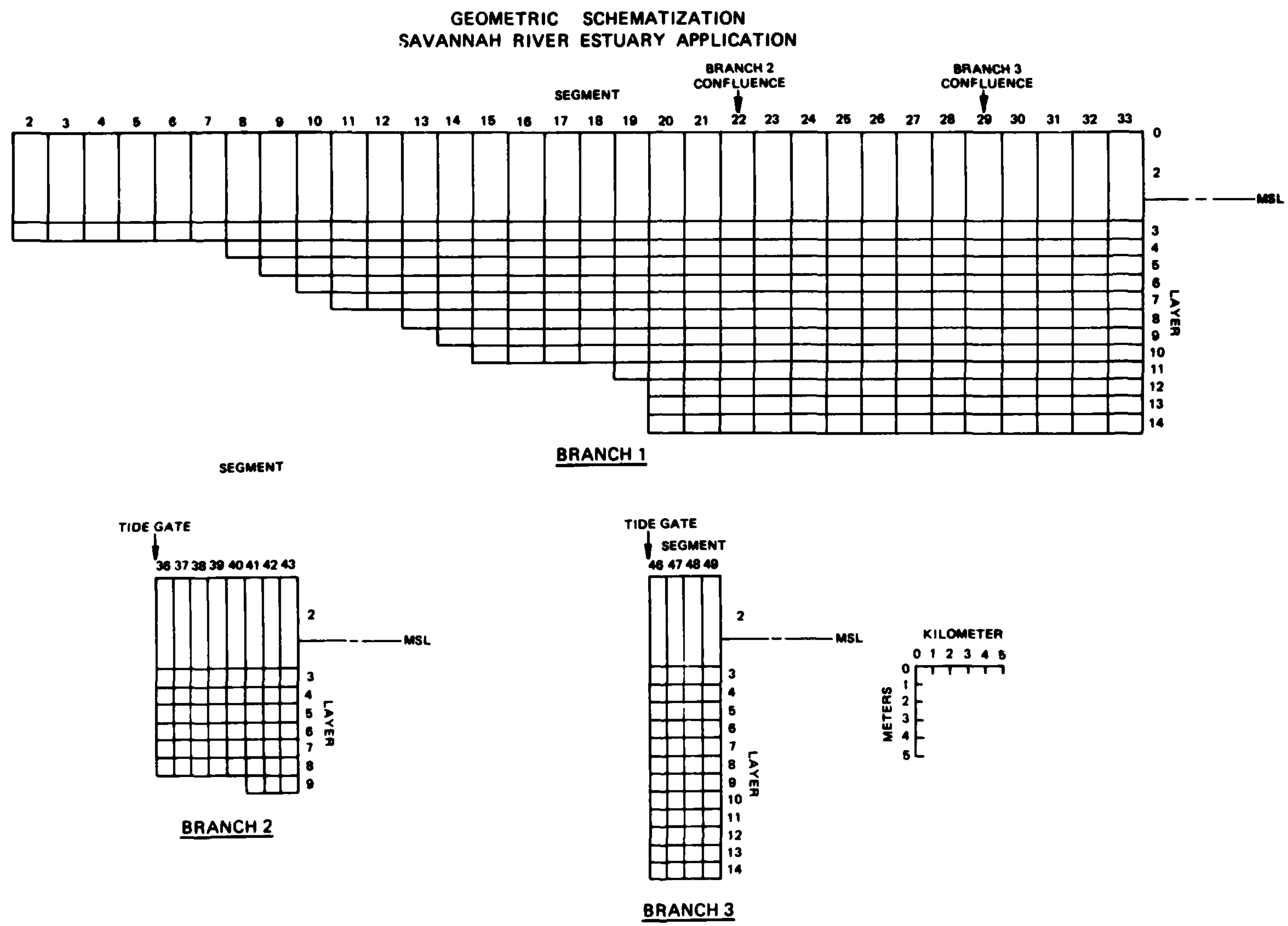

Figure 3. Vertical geometric schematization

RM	MSL,** ft
25.0	-2.9
29.0	-0.2
33.0	+2.7
36.9	+5.5
40.7	+8.0
45.7	+12.0

Tide Gate Characterization

19. The tide gate is located on Back River. The tide gate is controlled to open during the flood tide and close at high-water slack. The switching of the tide gate's position is automatically controlled by sensing changes in the water surface elevation.

20. The tide gate operation was simulated by defining Back River as two branches: Branch 2 upestuary and Branch 3 downestuary of the tide gate (Figures 2 and 3). Flow through the tide gate during the flood tide was simulated as a withdrawal from Branch 3 and an inflow into Branch 2. During ebb tide, withdrawals from Branch 3 and inflows into Branch 2 were specified equal to zero.

21. Flow through the tide gate was calculated assuming that the open tide gate could be modeled as a submerged weir. The bottom of the tide gate structure is located 4.145 m below MSL. The width of the structure is 183.5 m. The formulae selected were from King and Brater (1963). In reference to Figure 4, which is a schematization of the tide gate, the flow Q through the structure was calculated using the relationship:

$$Q = Q^* \left[1 - \left(\frac{H_2}{H_1} \right)^n \right]^{0.385} \qquad (1)$$

where

Q = discharge through the gate, m^3/sec

Q^* = discharge at the head H_1 computed from the equation for free discharge, m^3/sec

H_1 = head on the upstream side of the weir, m

H_2 = head on the downstream side of the weir, m

n = 1.5 = exponent in the free discharge equation

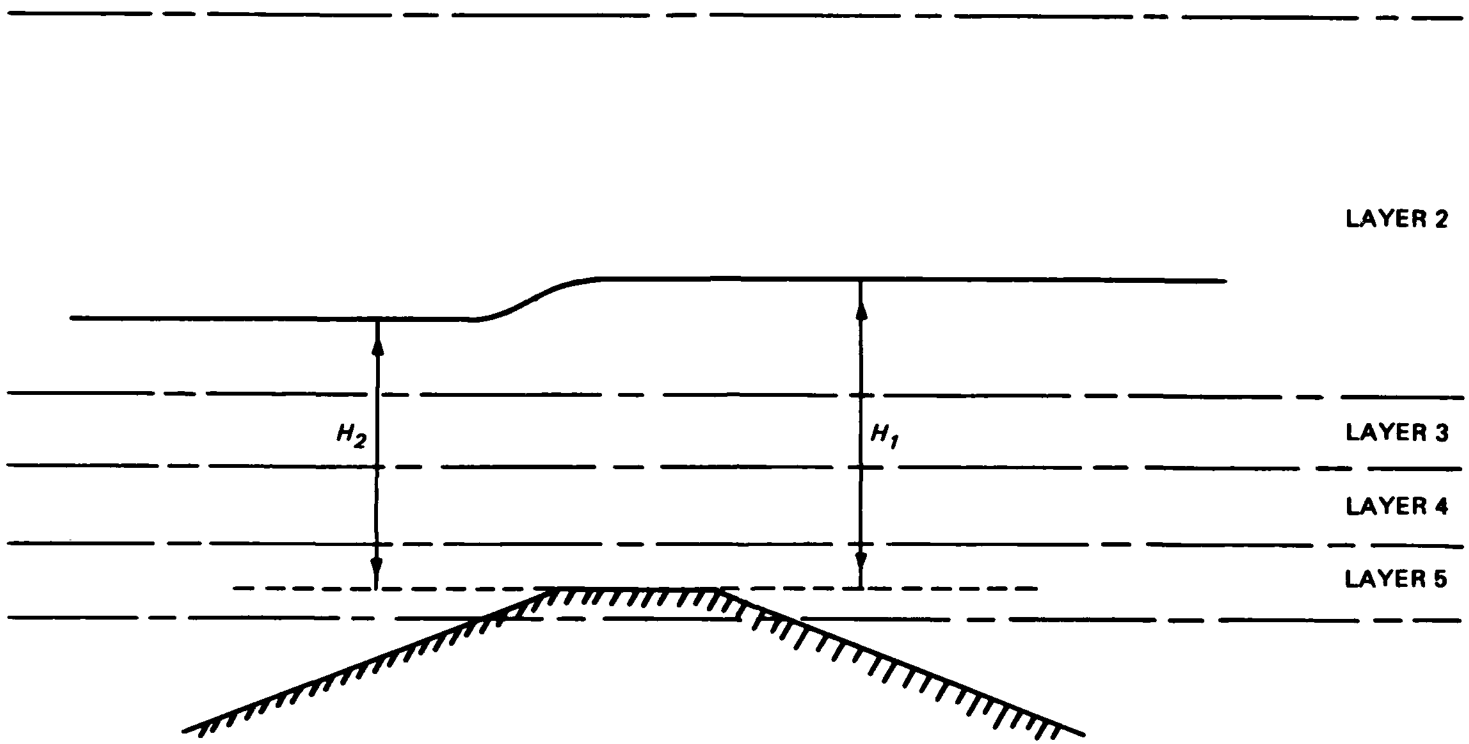

Figure 4. Tide gate schematization

The free discharge equation used was

$$Q^* = 183.5\ C\left(H_1\right)^n \tag{2}$$

where

$C = 2.0$ = discharge coefficient

$n = 1.5$

The head heights H_1 and H_2 were calculated based on the segment elevations of Branch 2 and Branch 3 adjacent to the tide gate structure. The withdrawals from Branch 3 were proportioned to layers 2 through 5 based on their cross-sectional area.

Constituent Reactions

22. The primary constituent of interest was DO. Salinity was simulated because gradients of this constituent affected the hydrodynamics and provided a means to calibrate the model for constituent transport.

23. Two model formulations were simulated. The first was a DO and BOD relationship, and the second included the nutrients nitrogen and phosphorus and the biological component algae.

24. Constituent model formulations are detailed in the report "CE-QUAL-W2: A Numerical Two-Dimensional, Laterally Averaged Model of Hydrodynamics and Water Quality; User's Manual" (Environmental and Hydraulics Laboratories 1986). The following discussion describes the constituent interpretation permitting specific application to the Savannah River estuary.

<u>Formulation 1: DO-BOD</u>

25. BOD was simulated as two components because identified oxygen demanding substances varied greatly in their decay rates. BOD due to effluents from the pulp and paper mill, secondary treated municipal sources, and the urban canal were simulated as one component (BOD), whereas the ferrous sulfate (Fe_2SO_4) effluent from American Cyanamid was simulated as a second component (BOD*). Both components were modeled assuming first-order decay but with different reaction rates.

26. Background BOD and BOD due to pulp and paper, secondary treated municipal, and urban canal effluents were simulated as constituent 5, and

BOD* was simulated as constituent 6 in CE-QUAL-W2. Constituent 5 is typically called labile dissolved organic matter (DOM) in CE-QUAL-W2, and constituent 6 is called refractory DOM. However, since the kinetic description of these two variables was identical to those required to simulate BOD and BOD* in this application, the only modification required was in the value of the kinetic coefficients and in the naming convention. This convention made use of the existing generality of CE-QUAL-W2. The specification of reaction rate coefficients permitted the characterization of appropriate pathways and reaction rates. The pertinent reaction rate coefficients for Formulation 1 are listed in Table 2.

27. Other constituents simulated were temperature, salinity (constituent 4), and DO (constituent 12). The interfacial DO exchange rate was computed according to O'Connor (1983). The transfer coefficients were based on intermediate (field average) scales. Reaction rates were modified by water temperature using the formulation of Thornton and Lessem (1978).

Formulation 2

28. Formulation 2 included salinity (constituent 4), BOD (constituent 5), algae (constituent 7), detritus (constituent 8), phosphorus (constituent 9), ammonia (constituent 10), nitrate + nitrate (constituent 11), and DO (constituent 12). BOD* effluent from American Cyanamid was simulated as a separate component (constituent 6) similar to Formulation 1.

Boundary Conditions

29. In order to model water, heat, and constituent budgets accurately through the simulation period, it was necessary to consider heat and light exchange through the water surface, water and constituent mass and heat advected in and out of the estuary, and DO exchange through the water surface and with the bottom sediments.

Meteorological data

30. Weather information was acquired from NOAA's Tape Deck No. 1440 WBAN Hourly Surface Observations for the Savannah Municipal Airport (Station No. 03822). Meteorological data were needed to compute equilibrium temperature (ETM), coefficient of surface heat exchange (CSHE), solar radiation (SRO), and wind shear at the water surface. The procedure used to prepare the meteorological data included: (a) extraction of only those data

Table 2

Reaction Rate Coefficients for Formulation 1

Parameter	Card	Value	Description*
TDOMDK	RI	0.3	Maximum labile DOM decay rate, 1/day (BOD decay rate)
TRFRDK	RJ	2.0	Maximum refractory DOM decay rate, 1/day (BOD* decay rate)
TDOMRF	RJ	0.0	Maximum rate at which labile DOM decomposes to refractory DOM, 1/day (a value of 0.0 was specified since there was no pathway between BOD and BOD*)
DOMCNT	RJ	1.0	Fraction of influent DOM that is labile**
DOMT1	RK	2.0	Lower temperature bound of DOM decay, °C (BOD and BOD*)
DOMT2	RK	20.0	Lower temperature bound of maximum DOM decay, °C (BOD and BOD*)
DOMK1	RK	0.12	Rate multiplier corresponding to DOMT1 (BOD and BOD*)
DOMK2	RR	0.98	Rate multiplier corresponding to DOMT2 (BOD and BOD*)
O2DOM	RO	1.0	Oxygen stoichiometric equivalent for DOM decay (BOD and BOD*)

* The first description represents the general naming convention in CE-QUAL-W2, whereas the description in parentheses represents the convention used in this implementation.

** The code permits input of DOM with subsequent partitioning between labile and refractory components. The application explicitly specified the inputs of labile (BOD) and refractory (BOD*) dissolved organic matter; thus, no additional partitioning was required.

needed as input to the model, (b) flagging missing data, (c) translation overpunch data, and (d) conversion of the hourly observation data to daily averages. The computer codes described in Environmental Laboratory (1982) were modified and used for meteorological data preparation.

31. The computations of equilibrium temperature, coefficient of surface heat exchange, and solar radiation were based on the Heat Exchange Program (Program No. 722-F5-E1010) available from the US Army Engineer District,

Baltimore. Code modifications were necessary to ensure units consistent with the model requirements.

External flow boundary conditions

32. External flow boundary conditions consisted of freshwater flow of the Savannah River at the upestuary boundary, two withdrawals of river water, and six point source discharges. Each inflow required a magnitude, temperature, and concentration for each modeled constituent. The withdrawals required specification of magnitude.

33. Freshwater flow. The US Geological Survey (USGS) publishes water-discharge records at Clyo, Ga., at RM 60.9 (USGS 1980), which is 26 km upstream from the upestuary boundary. The discharge during August 1980 was rather uniform averaging 204 m^3/sec with a maximum and minimum of 248 and 173 m^3/sec, respectively. The flow increase between the gage and the model's upestuary boundary was based on the ratio of drainage areas of 1.072 (LMS 1983). Freshwater flows were updated daily.

34. The diel study provided freshwater inflow estimates of temperature, DO, and conductivity; the center-line study results of the upestuary station at Ebenezer Landing provided freshwater inflow estimates of the nutrients NH_4, NO_2 + NO_3, total P, and BOD_5. Linear interpolation between sampling dates provided daily updates.

35. Withdrawals. Two withdrawals of water were simulated in the model application: the Savannah Water Works (SWW) Surface Filtration Plant (RM 29, Segment 15) and the Beaufort-Jasper Water Authority (BJWA) Freshwater Canal (RM 39, Segment 7). The SWW withdrawal of 1.54 m^3/sec and the BJWA withdrawal of 0.26 m^3/sec were assumed constant.

36. Wasteloads. Point source discharges were simulated as tributaries. Three industries (American Cyanamid, Union Camp, and Continental Group), a municipal sewage treatment plant (President Street STP), and two urban canals (Springfield and Pipemakers) were included as point source loads. Effluent characteristics were abstracted from LMS (1983) and tabulated in Table 3.

37. An ultimate BOD to BOD_5 factor of 1.5 was assumed for the President Street STP and the two urban canals. An ultimate BOD to BOD_5 factor of 2.5 was selected for the effluent from the Union Camp and Continental Group pulp and paper mills. These estimates were abstracted from LMS (1983).

Table 3

Point Source Discharges Savannah River Estuary

Source	RM	Segment	Discharge m^3/sec	Ultimate BOD g/m^3	DO g/m^3	Salinity ppt	Temperature °C
American Cyanamide (chemical manufacturer)	10.4	30	1.1	37.54*	0.0	1.0	28.0
President Street STP (municipal STP)	12.3	28	0.6	27.96	3.5	1.0	28.0
Union Camp (pulp and paper)	16.2	25	1.5	98.25	3.0	1.0	28.0
Continental Group (pulp and paper)	21.0	21	1.2	68.67	3.0	1.0	28.0
Springfield (urban canal)	14.8	26	0.4	19.27	3.0	1.0	28.0
Pipemakers (urban canal)	18.5	23	0.4	4.00	1.4	1.0	28.0

* Represent ultimate DO requirement for $Fe^{++} \rightarrow Fe^{+++}$; modeled separately.

38. American Cyanamid did not discharge organic wastewater, but the chemical manufacturer did discharge ferrous sulfate. The oxidation of Fe^{++} to Fe^{+++} occurs rapidly and depletes the DO of the receiving waters. LMS (1983) simulated the American Cyanamid iron wasteload as an immediate oxygen demand using a DO deficit in their model. In contrast, the present study simulated ferrous sulfate as a separate component, undergoing first-order decay requiring DO similar to BOD, but at an increased rate.

External head boundary elevation

39. A Fisher and Porter Type 150 surface elevation level recorder was located at the downstream study boundary at RM 5.9. The gage data were used to specify the downstream external head boundary elevation. Analysis of the tide gage data consisted of data editing to fill in short sequences of missing data, filtering to remove high- and low-frequency trends from the data, and harmonic analysis for tidal constituents.

40. Data editing. For single missing data values, an average of adjacent tidal heights was substituted. For longer intervals of missing data, the preceding tidal cycle water surface elevations were superimposed over the missing interval, and tidal heights were visually estimated. The manual preparation of tide gage data resulted in a tidal record extending from 24 July 1980 at 1400 EST through 27 August 1980 at 0654 EST with 8,100 observations.

41. Filtering. A digital band-pass filter was applied to attenuate high and low frequencies. The period range considered in the harmonic analysis was approximately 12 to 24 hr. Because of the large tidal range, absence of major passing synoptic weather fronts, and uniform freshwater flow during the recording period, filtering was not mandatory. However, filtering did result in smaller deviations between measured and predicted elevations because noise not accounted for in the descriptive equation for water surface elevation was attenuated. An eight-pole Butterworth filter, characterized by a smooth power gain with maximum flatness in the passband and the stop band along with a reasonably sharp cutoff, was used (Outlaw and Butler 1982). Half-power frequencies were 4.63×10^{-5} Hz and 7.72×10^{-6} Hz or 6 hr and 36 hr, respectively.

42. Harmonic analysis. The arithmetic mean of the tide record was subtracted from each datum, and the result was interpreted as a deviation from MSL, the datum used in the Savannah River Estuary study.

43. The elevation of the Savannah River Estuary tide was represented by

$$h(t) = \sum_{j=1}^{m} A_j \cos_j (\omega \; t_j + \phi \;) \tag{3}$$

where

h = elevation at time t

t = time from some initial time (1400, 24 July 1980, in the study)

m = number of tidal constituents

A_j = amplitude of the j^{th} tidal constituent

ω_j = angular frequency of the j^{th} tidal constituent

ϕ_j = phase of the j^{th} tidal constituent

An observed surface elevation datum $h_i(t)$ can be represented by

$$h_i(t) = \sum_{j=1}^{m} (a_j \cos \omega_j t + b_j \sin \omega_j t) + \varepsilon_i(t) \tag{4}$$

where

a_j, b_j = coefficients

$\varepsilon_i(t)$ = error in observed datum i

For each tidal constituent, the amplitude A_j and the phase ϕ_j can be determined from

$$A_j = \left(a_j^2 + b_j^2\right)^{1/2} \tag{5}$$

$$\phi_j = \arctan\left(\frac{b_j}{a_j}\right) \tag{6}$$

44. A least squares analysis was conducted to estimate the coefficients a_j and b_j, which minimized the sum of squares of the $N = 8{,}100$ error terms

$$\binom{\min}{a_j, b_j} \sum_{i=1}^{N} \epsilon_i(t)^2 \qquad (7)$$

The M_2, N_2, S_2, K_1, O_1, P_1, and K_2 tidal harmonics were estimated. The tidal harmonic constituents represent selected effects of the gravitational effects of the earth, moon, and sun. The subscript 1 represents diurnal periods, and the subscript 2 represents semidiurnal periods.

Result

45. Component amplitudes and phases for the tidal record are tabulated in Table 4. The observed, filtered, and simulated tidal elevations are displayed in Figure 5. Equation 3, using the tidal constituent values in Table 4, was used in the subroutine TVDS to provide the downstream external head boundary elevation (ELR) for Branch 1.

External head boundary profiles

46. On 6, 13, 19, and 26 August 1980, surface-to-bottom profiles of temperature, DO, and conductivity were made at 1-m intervals at the downstream boundary. Water samples for NH_3, $NO_2 + NO_3$, total P, and BOD_5 analyses were

Table 4

Calculated Tidal Components

Tidal Component	Reference Time	Period, h	Amplitude, m	Phase, rad
M_2	24 July 1980	12.421	1.030	1.892
N_2	1400 EST	12.658	0.205	-0.061
S_2		12.000	0.228	-2.533
K_1		23.934	0.046	0.497
O_1		25.819	0.080	1.073
P_1		24.066	0.115	1.437
K_2		11.967	0.099	1.100

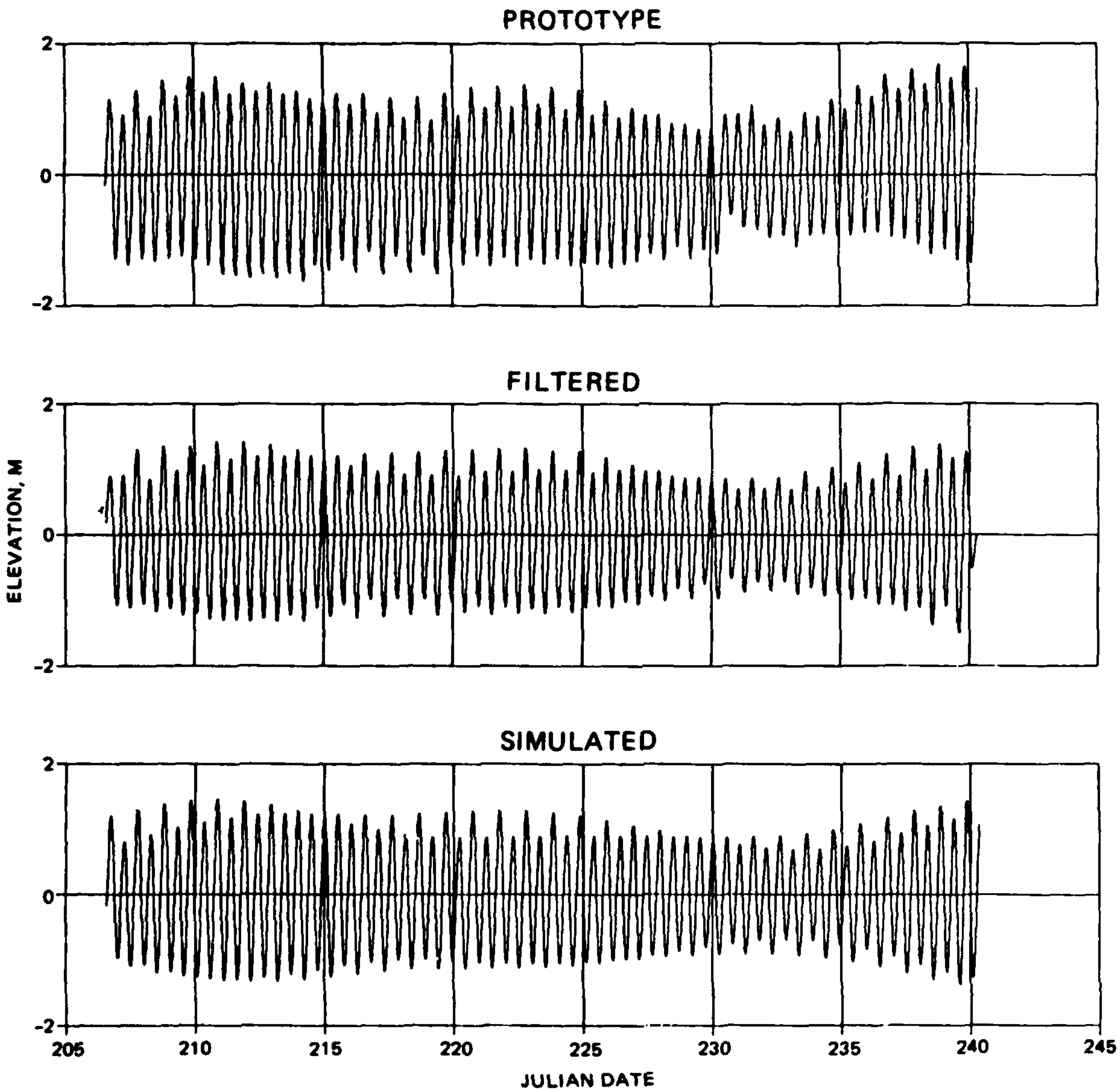

Figure 5. Prototype, filtered, and simulated water surface elevation

collected at four depths: 1 m below the surface, 1 m above the bottom, and two depths intermediate to surface and bottom. Profiles were made, and samples were collected every hour for 13 consecutive hours.

47. Interest was in both intratidal and intertidal variations over the month. The desired external head boundary profiles required intratidal updates extending over the entire month and at a vertical resolution corresponding to the model layers. Models specifying external head boundary

concentrations were needed to specify concentrations for times and dates for which no data existed.

48. Preparation of the profile data consisted of conversion of conductivity to salinity, relating sample depth to MSL, interpolation over model grid layers, and harmonic analysis.

49. Conversion of conductivity to salinity. Conversion of conductivity (mmho/cm) to salinity (ppt) was achieved by using a piecewise linear relationship abstracted from a nomogram published by Hydrolab (undated). The relationship used was:

Conductivity, mmho/cm	Salinity
COND < 10	SAL = 0.55*COND
10 ≤ COND < 20	SAL = 0.62*COND-0.7
20 ≤ COND < 30	SAL = 0.67*COND-1.7
30 ≤ COND < 40	SAL = 0.69*COND-2.3
40 ≤ COND < 50	SAL = 0.75*COND-4.7
50 ≤ COND	SAL = 0.74*COND-4.2

50. Relation of sample depth to MSL. Samples were collected at depths relative to the water surface. However, the water surface elevation changed within the 13-hr sampling period as well as between periods. Equation 3 with tidal constituents for the tide gauge at RM 5.9 was used to specify the water surface elevation at the time of sample collection and permitted specification of sample depth relative to MSL.

51. Interpolation over model grid. Linear interpolation was used to assign a constituent concentration to each of the model grid layers. Grid layers deeper than measured data were assigned values equal to the adjacent interior measured data.

52. Harmonic analysis. Examination of the data revealed periodicities for all constituents and a linear decrease with time for temperature between dates. The average tidal period for August 1980 abstracted from (NOAA) Tide Tables (NOAA 1980) for Savannah was 12.42 hr, the period of the M_2 tidal constituent. Therefore, least squares were used to fit a sinusoidal with a period of 12.42 hr (angular frequency = 0.5059 rad/hr) to the observed data for each layer. A linear regression term was included for temperature.

53. The model used for temperature was

$$T = T_o + \beta t + A \cos (\omega t - \phi) \quad (8)$$

For salinity, DO, BOD_5, NH_4, NO_3, and P, the model used was

$$C = C_o + A \cos(\omega t - \phi) \qquad (9)$$

where

T = temperature, °C

T_o = intercept, °C

β = regression coefficient, °C/hr

t = time, hr

C = constituent concentration, ppt or g/m^3

C_o = constituent mean concentration, ppt or g/m^3

A = amplitude, °C or g/m^3

ω = angular frequency, rad/hr

ϕ = phase, rad

54. The Naval Surface Weapons Center (NSWC) (1981) least squares subroutines were used to fit the selected models.

55. In Table 5 are listed the intercept, regression coefficient, amplitude, phase, and R^2 value of the temperature model for each layer. The R^2, or coefficient of determination, measures the portion of the variation in the temperature that is attributed to the model rather than to random error. R^2 is defined as follows:

$$R^2 = 1.0 - \left[\frac{\left(T_i - T_i\right)^2}{\left(T_i - \bar{T}\right)^2} \right] \qquad (10)$$

where

T_i = observed temperature datum

$\hat{T}_i$ = predicted temperature based on model

$\bar{T}$ = mean of temperature data

56. In Tables 6 through 11 are listed the mean, amplitude, phase, and R^2 value for salinity, DO, BOD_5, NH_4-N, $NO_2 + NO_3$-N, and total-P.

57. Examination of Tables 5 through 11 reveals that temperature and salinity were adequately characterized by the sinusoidal function, that the

Table 5

Intercept, Regression Coefficient, Amplitude, Phase, and Coefficient of Determination (R^2) for the Temperature Profile Head Boundary Condition

Layer	Intercept °C	Regression Coefficient 10^{-2} °C/hr	Amplitude °C	Phase* rad	R^2
2	30.4	-0.459	0.27	-0.21	0.73
3	30.4	-0.482	0.19	-0.36	0.81
4	30.4	-0.479	0.17	-0.31	0.83
5	30.4	-0.476	0.12	-0.59	0.85
6	30.3	-0.464	0.07	-0.38	0.85
7	30.3	-0.465	0.04	0.14	0.83
8	30.4	-0.497	0.06	-2.20	0.84
9	30.4	-0.496	0.09	-2.22	0.84
10	30.4	-0.495	0.10	-2.02	0.82
11	30.5	-0.501	0.10	-1.81	0.83
12	30.4	-0.498	0.11	-2.01	0.84
13	30.4	-0.503	0.11	-2.06	0.85
14	30.4	-0.513	0.10	-1.91	0.85

* Reference time = 1 August 1980, 0000 EST.

Table 6

Mean, Amplitude, Phase, and Coefficient of Determination (R^2) for the Salinity Profile Head Boundary Condition

Layer	Mean ppt	Amplitude ppt	Phase* rad	R^2
2	13.5	4.6	0.05	0.65
3	13.9	5.0	0.05	0.72
4	14.6	5.5	0.04	0.75
5	15.7	6.0	0.05	0.78
6	16.8	6.2	0.07	0.77
7	18.1	5.7	0.15	0.75
8	19.2	5.1	0.23	0.70
9	20.0	4.5	0.25	0.63
10	21.0	3.8	0.28	0.55
11	21.3	3.6	0.26	0.56
12	21.6	3.1	0.32	0.49
13	22.0	2.9	0.40	0.45
14	22.2	2.7	0.48	0.42

* Reference time = 1 August 1980, 0000 EST.

Table 7

Mean, Amplitude, Phase, and Coefficient of Determination (R^2) for the DO Profile Head Boundary Condition

Layer	Mean g/m^3	Amplitude g/m^3	Phase* rad	R^2
2	4.2	0.5	0.10	0.43
3	4.1	0.4	0.02	0.42
4	4.0	0.4	0.05	0.46
5	3.9	0.4	0.14	0.46
6	3.8	0.4	0.18	0.43
7	3.7	0.4	0.14	0.49
8	3.7	0.4	0.13	0.51
9	3.7	0.4	0.15	0.50
10	3.6	0.4	0.24	0.53
11	3.6	0.4	0.26	0.51
12	3.6	0.4	0.26	0.51
13	3.6	0.4	0.29	0.48
14	3.6	0.4	0.32	0.43

* Reference time = 1 August 1980, 0000 EST.

Table 8

Mean, Amplitude, Phase, and Coefficient of Determination (R^2) for the BOD_5 Profile Head Boundary Condition

Layer	Mean g/m^3	Amplitude g/m^3	Phase* rad	R^2
2	1.2	0.3	-0.08	0.19
3	1.1	0.2	-0.07	0.24
4	1.1	0.2	0.01	0.24
5	1.1	0.2	0.00	0.24
6	1.1	0.2	-0.18	0.26
7	1.2	0.2	-0.42	0.26
8	1.2	0.2	-0.61	0.23
9	1.2	0.2	-0.71	0.20
10	1.3	0.2	-0.82	0.17
11	1.3	0.2	-0.87	0.19
12	1.4	0.3	-0.92	0.19
13	1.4	0.3	-0.92	0.19
14	1.4	0.3	-0.97	0.18

* Reference time = 1 August 1980, 0000 EST.

Table 9

Mean, Amplitude, Phase, and Coefficient of Determination (R^2) for the NH_4-N Profile Head Boundary Condition

Layer	Mean g/m^3	Amplitude g/m^3	Phase* rad	R^2
2	0.08	0.01	3.10	0.05
3	0.08	0.01	-3.00	0.08
4	0.08	0.01	-2.90	0.10
5	0.08	0.01	-2.95	0.15
6	0.08	0.01	-3.13	0.17
7	0.09	0.02	2.48	0.08
8	0.09	0.03	2.17	0.06
9	0.10	0.04	2.02	0.06
10	0.10	0.05	1.94	0.06
11	0.10	0.04	1.92	0.06
12	0.09	0.03	1.88	0.07
13	0.09	0.02	1.81	0.07
14	0.08	0.01	1.70	0.05

* Reference time = 1 August 1980, 0000 EST.

Table 10

Mean, Amplitude, Phase, and Coefficient of Determination (R^2) for the NO_2 + NO_3-N Profile Head Boundary Condition

Layer	Mean g/m^3	Amplitude g/m^3	Phase* rad	R^2
2	0.31	0.05	-3.02	0.22
3	0.30	0.07	-3.06	0.37
4	0.28	0.08	-3.05	0.51
5	0.27	0.09	-3.06	0.63
6	0.26	0.11	-3.06	0.69
7	0.24	0.11	-3.07	0.67
8	0.21	0.11	-3.08	0.62
9	0.19	0.10	-3.05	0.55
10	0.18	0.09	-3.01	0.48
11	0.17	0.08	-2.98	0.46
12	0.16	0.08	-2.94	0.43
13	0.15	0.07	-2.91	0.39
14	0.15	0.07	-2.87	0.34

* Reference time = 1 August 1980, 0000 EST.

Table 11

Mean, Amplitude, Phase, and Coefficient of Determination (R^2) for the Total-P Profile Head Boundary Condition

Layer	Mean g/m^3	Amplitude g/m^3	Phase* rad	R^2
2	0.07	0.01	-3.00	0.27
3	0.07	0.01	-2.76	0.11
4	0.07	0.01	-2.60	0.05
5	0.08	0.00	-1.86	0.02
6	0.08	0.01	-1.26	0.05
7	0.08	0.01	-1.13	0.10
8	0.09	0.02	-1.04	0.13
9	0.10	0.02	-0.89	0.16
10	0.11	0.03	-0.94	0.21
11	0.12	0.05	-1.04	0.21
12	0.14	0.06	-1.11	0.19
13	0.16	0.07	-1.16	0.18
14	0.17	0.07	-1.28	0.17

* Reference time = 1 August 1980, 0000 EST.

sinusoidal function accounts for 45 percent of the variability of DO and $NO_2 + NO_3$, and that the selected sinusoidal function poorly fits the BOD, NH_4, and P data. In Figures 6 through 25, prototype and simulated data values for temperature, salinity, BOD_5, and DO are displayed.

Sediment oxygen demand (SOD)

58. SOD demand rates were determined at RM 5.9 (Segment 33), RM 16.3 (Segment 25), and RM 21.5 (Segment 21) from 1 through 5 October 1980 (Table 12). The results were linearly interpolated over the model segments assuming 1.2 $g/m^2/day$ for Segment 2.

Table 12

Sediment Oxygen Demand (SOD)

Segment	Mean Rate, O_2 $g/m^2/day$
21	1.7
25	2.9
33	1.2

Initial Conditions

59. Initial conditions consist of water surface elevation, temperature, and constituent concentrations corresponding to the simulation starting time. The simultaneous solution of the combined momentum and continuity equations establishes a consistent flow field within a few wave travel times down the estuary; however, the establishment of a conservative constituent field consistent with the applied boundary conditions requires an amount of time approaching the residence time (Buchack and Edinger 1982).

60. Initial conditions must be specified for each model cell. The procedure used was to initialize all cells to one constituent value, simulate for a period of time sufficient for the constituent field to equilibrate to the boundary conditions, and use the resulting simulated cell constituent values as initial conditions for subsequent runs. An extended simulation with monitoring of transient cell constituent concentrations provided an estimate of

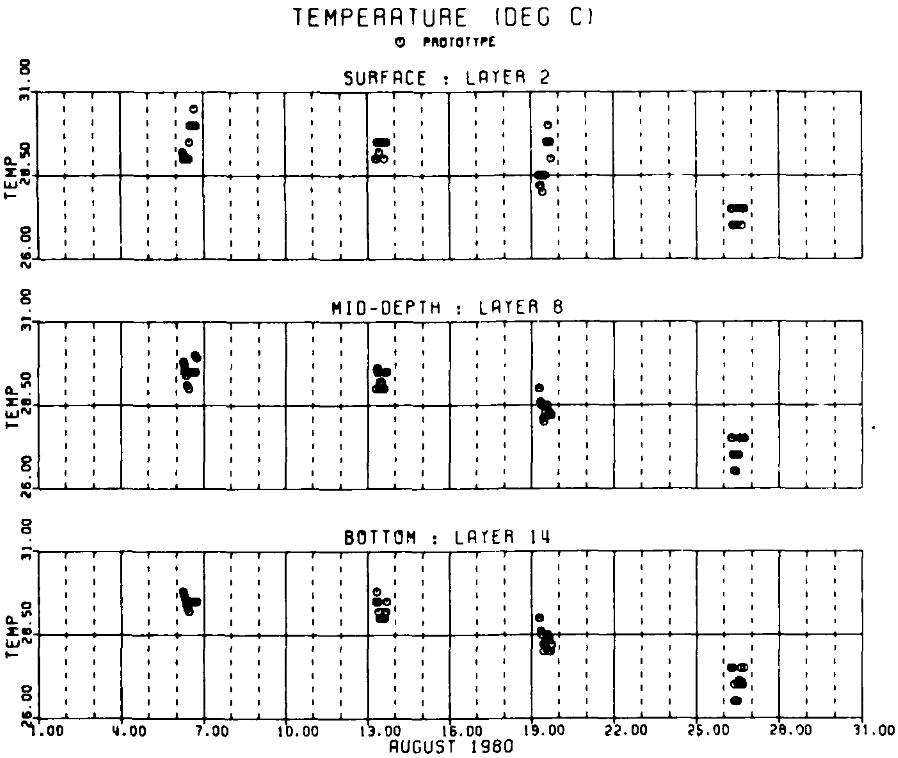

Figure 6. Measured temperatures, August 1980

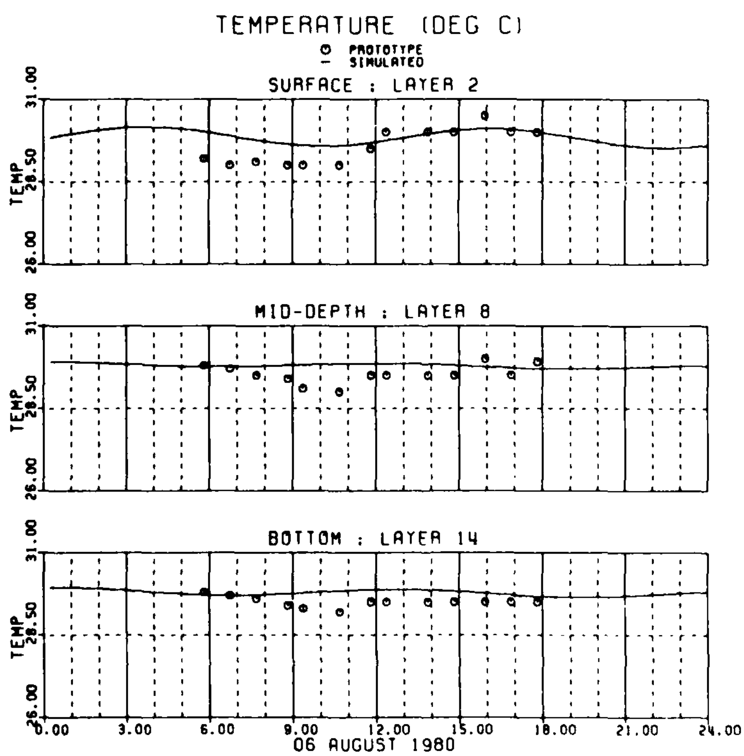

Figure 7. Measured and calculated temperatures, 6 August 1980

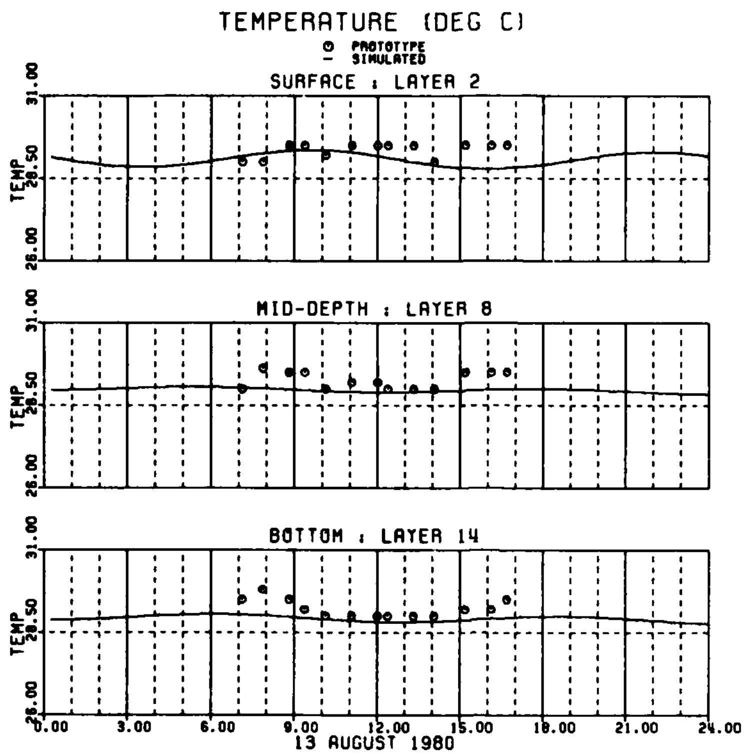

Figure 8. Measured and calculated temperatures, 13 August 1980

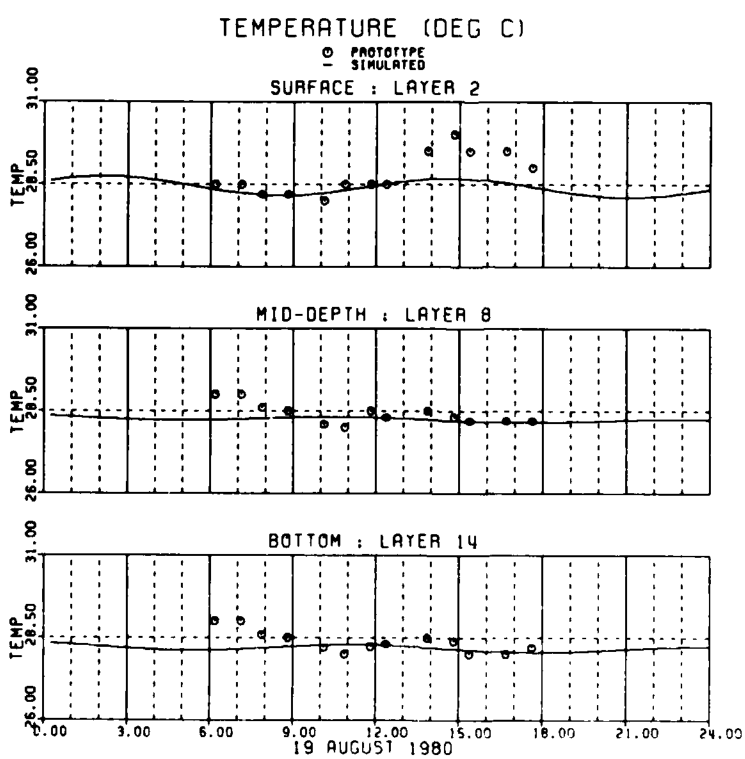

Figure 9. Measured and calculated temperatures, 19 August 1980

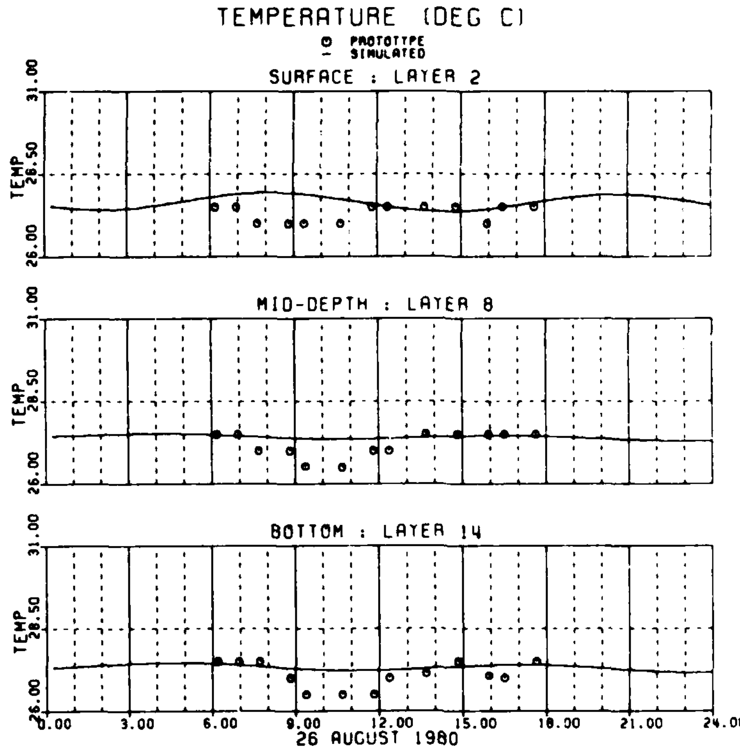

Figure 10. Measured and calculated temperature, 26 August 1980

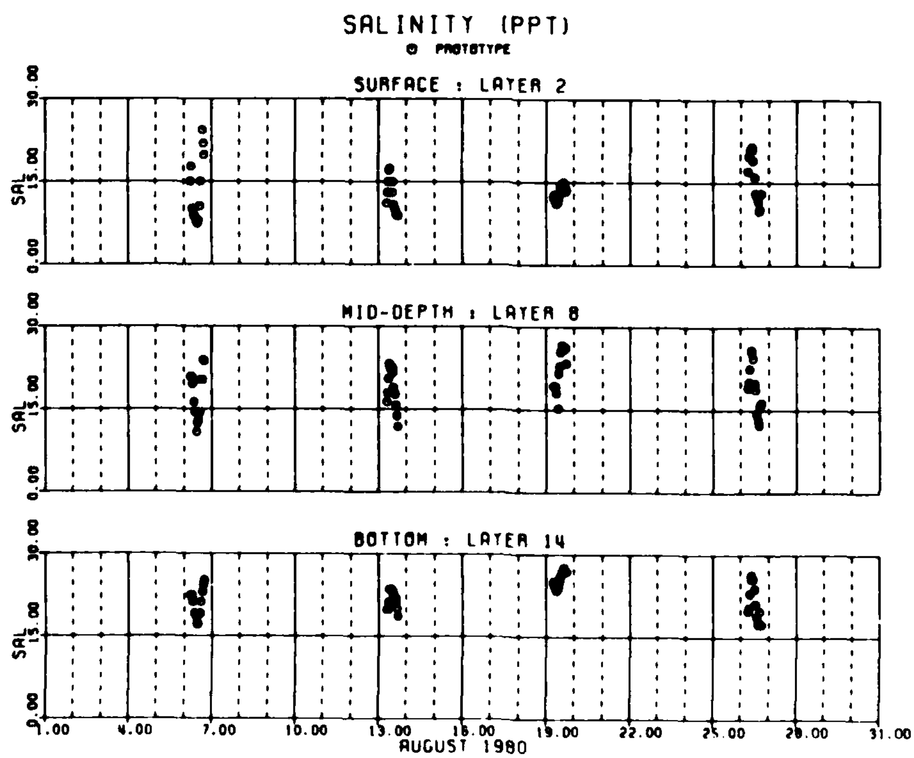

Figure 11. Measured salinity, August 1980

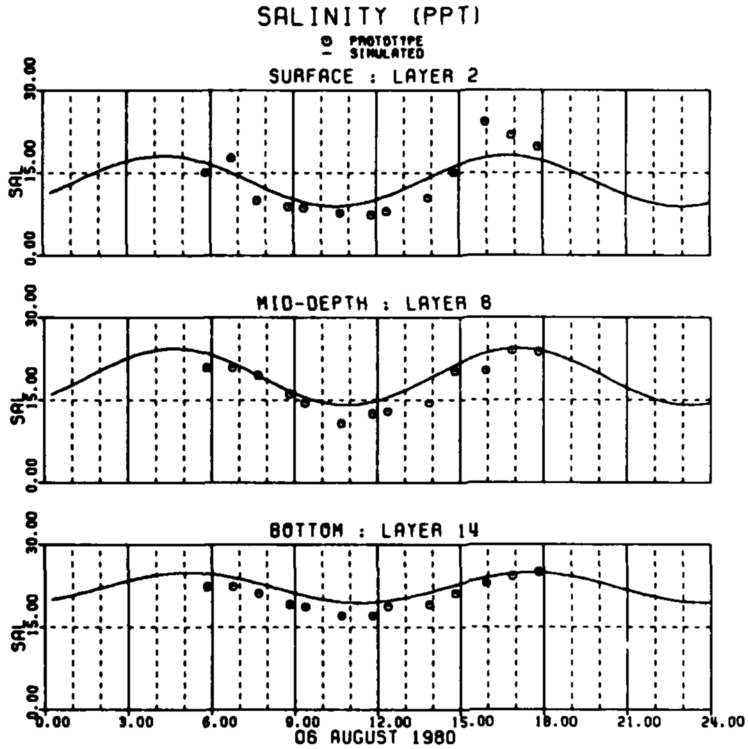

Figure 12. Measured and calculated salinity, 6 August 1980

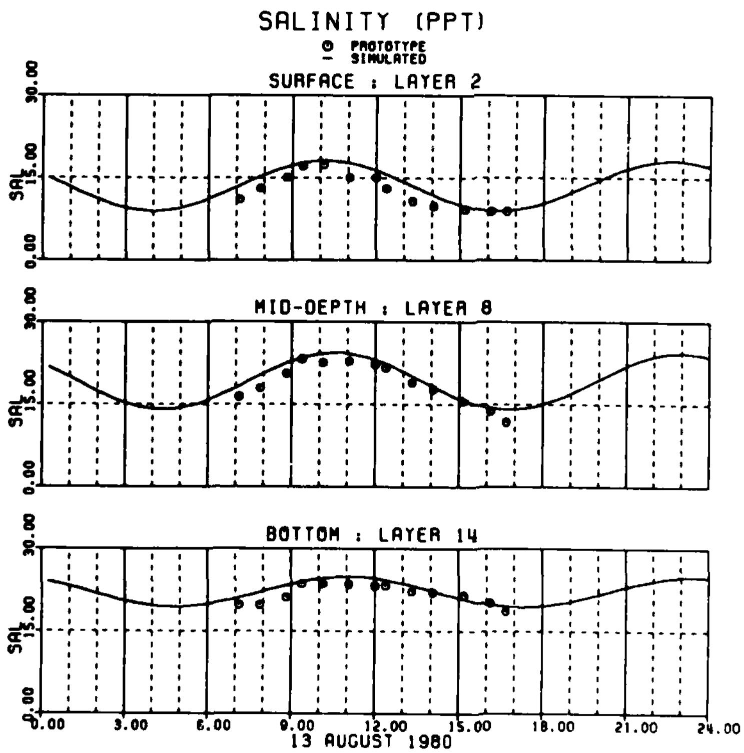

Figure 13. Measured and calculated salinity, 13 August 1980

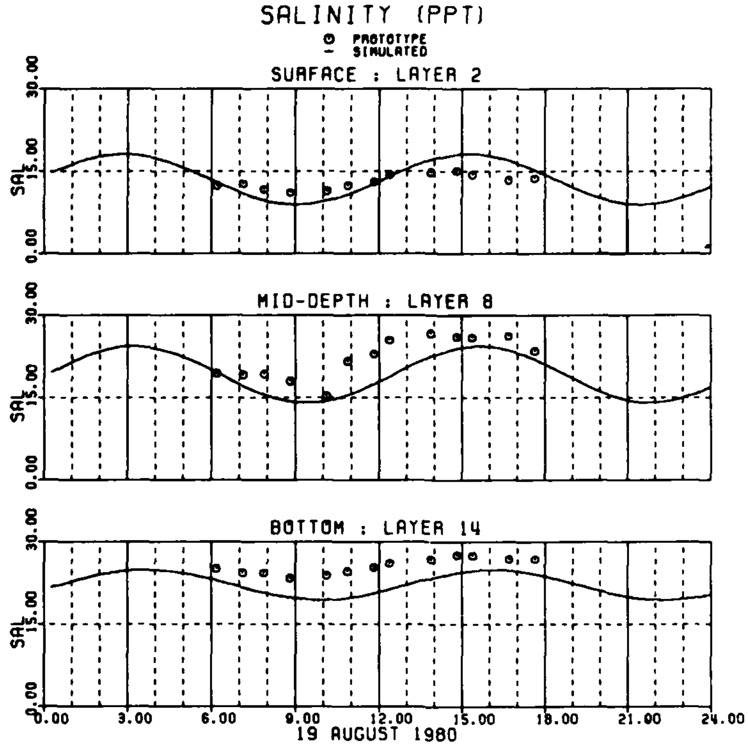

Figure 14. Measured and calculated salinity, 19 August 1980

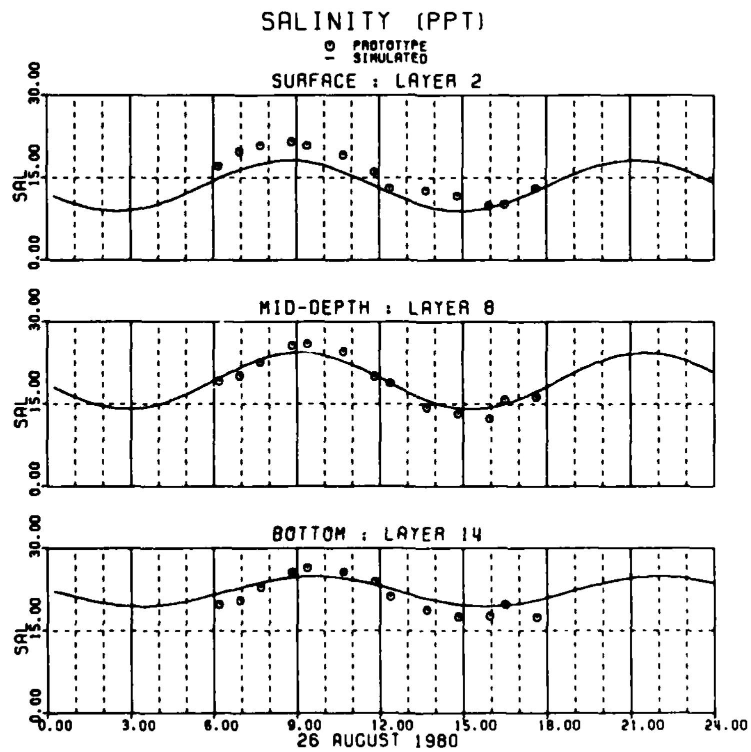

Figure 15. Measured and calculated salinity, 26 August 1980

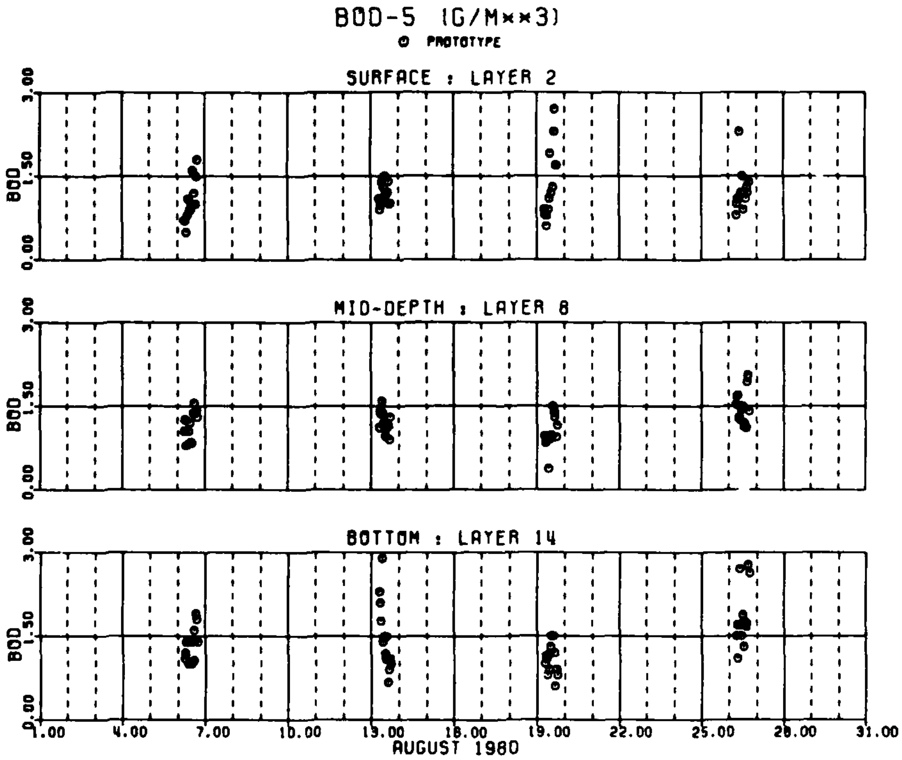

Figure 16. Measured BOD_5, August 1980

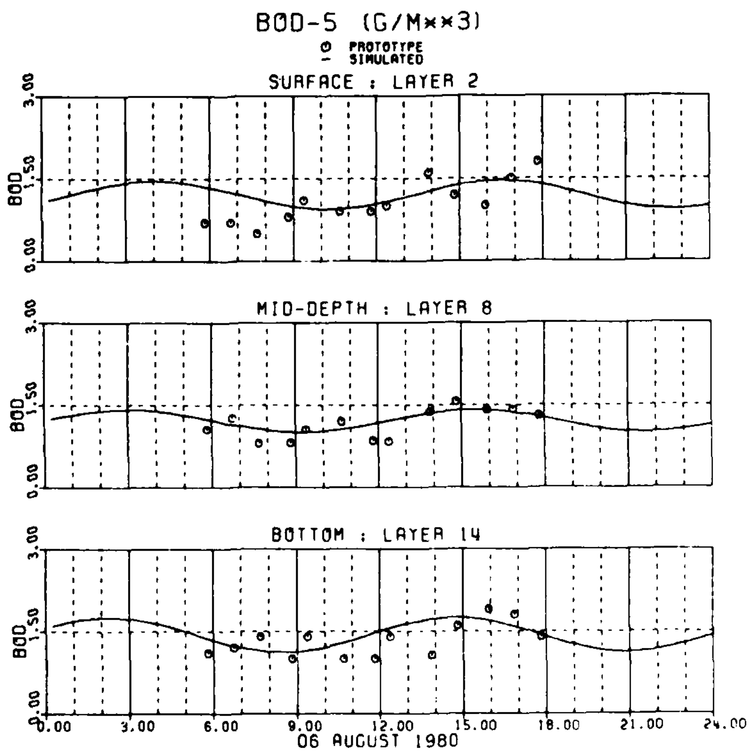

Figure 17. Measured and calculated BOD_5, 6 August 1980

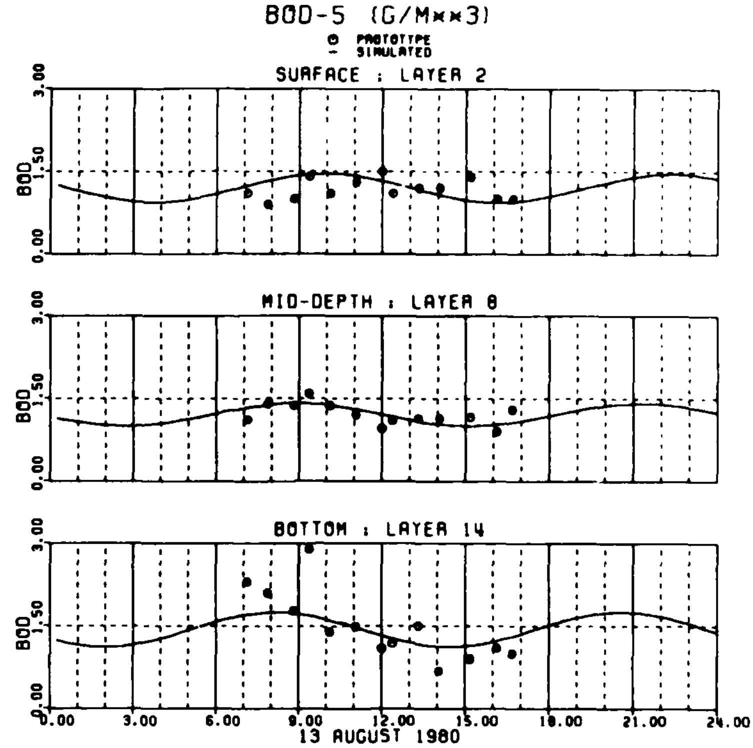

Figure 18. Measured and calculated BOD_5, 13 August 1980

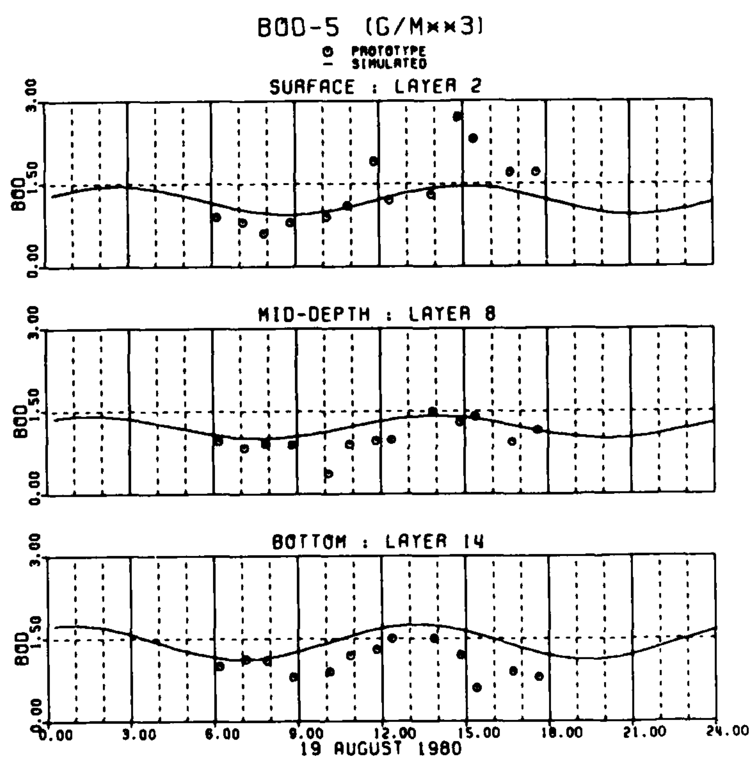

Figure 19. Measured and calculated BOD_5, 19 August 1980

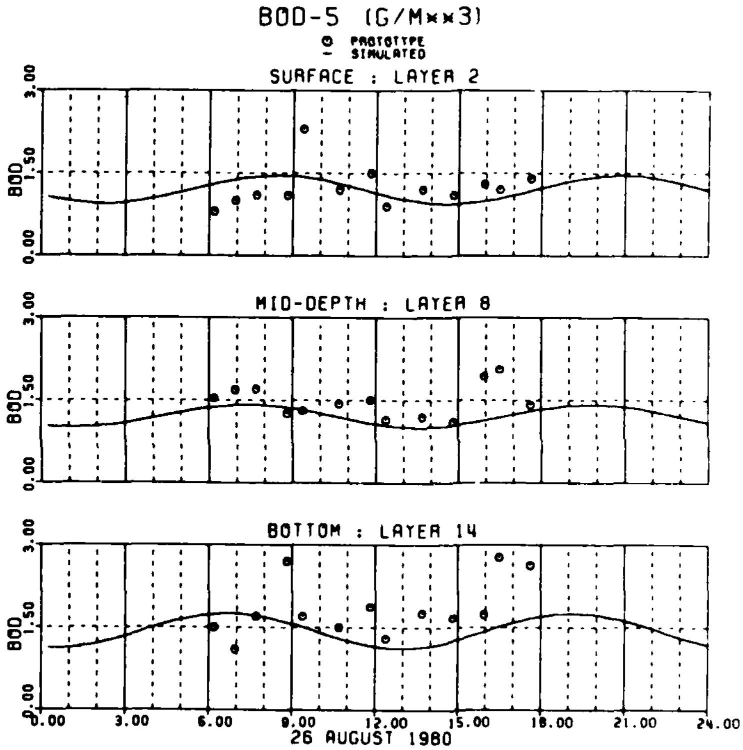

Figure 20. Measured and calculated BOD_5, 26 August 1980

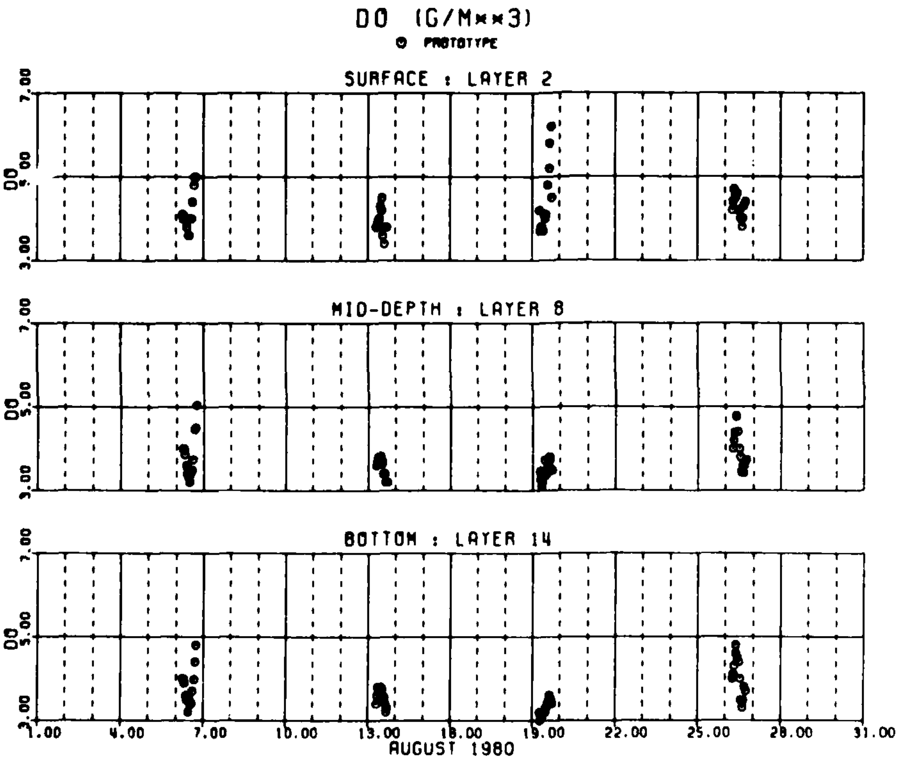

Figure 21. Measured DO, August 1980

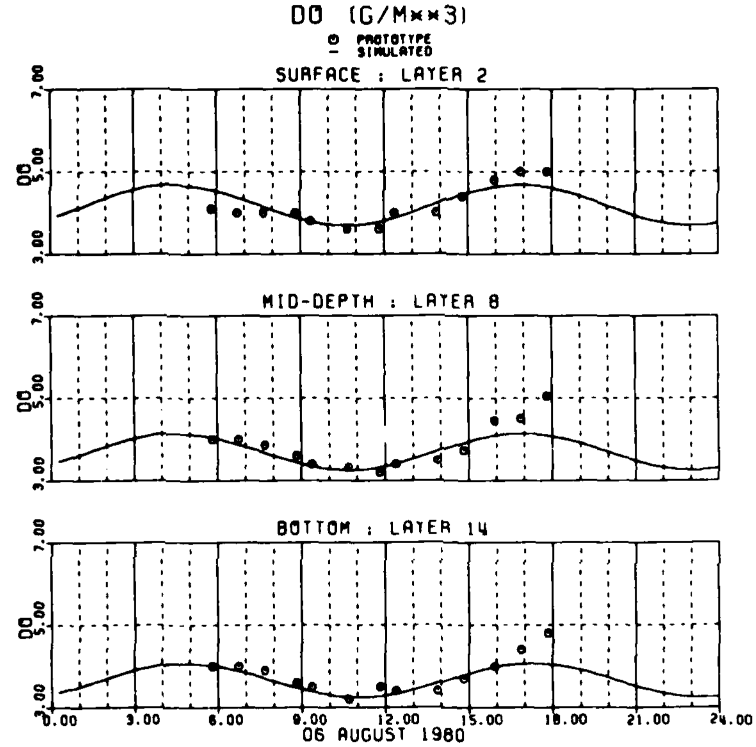

Figure 22. Measured and calculated DO, 6 August 1980

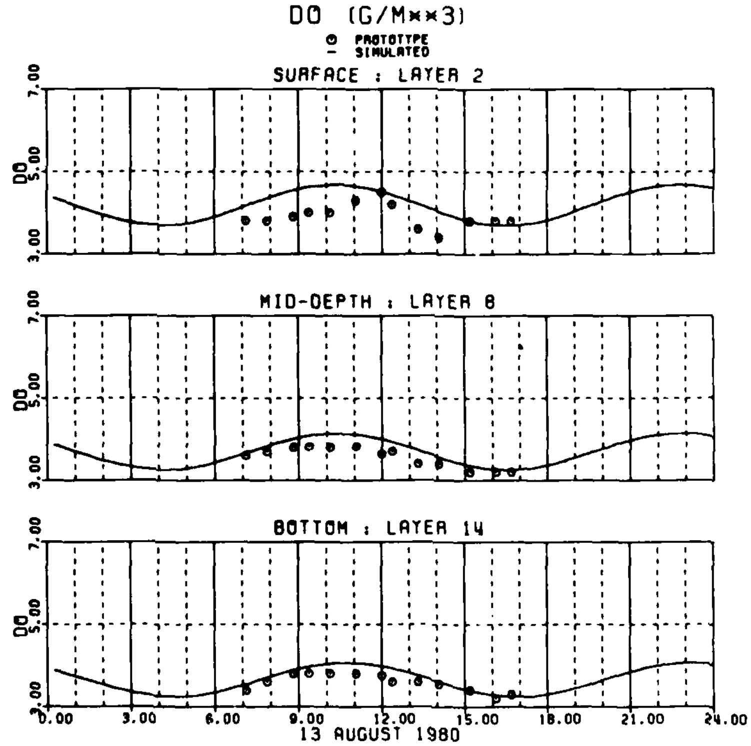

Figure 23. Measured and calculated DO, 13 August 1980

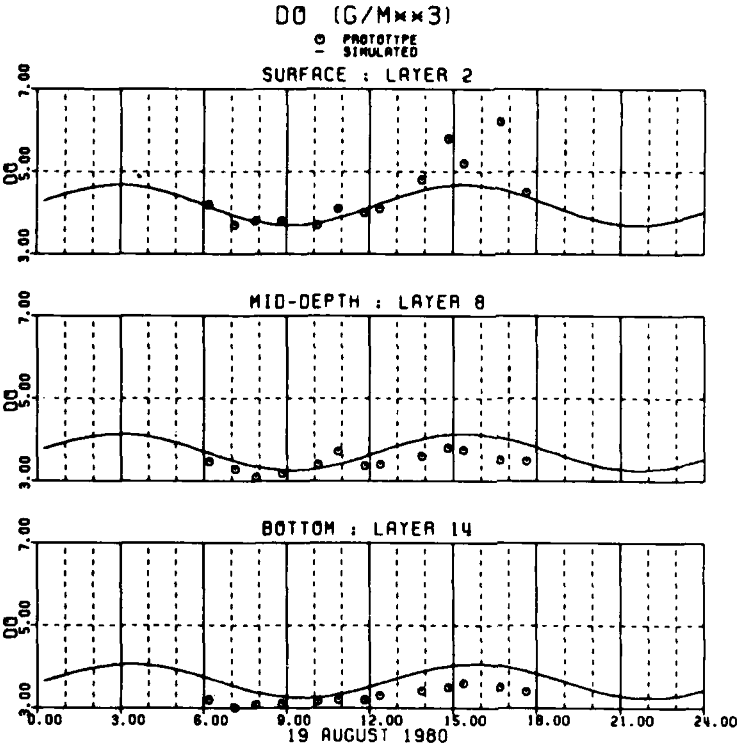

Figure 24. Measured and calculated DO, 19 August 1980

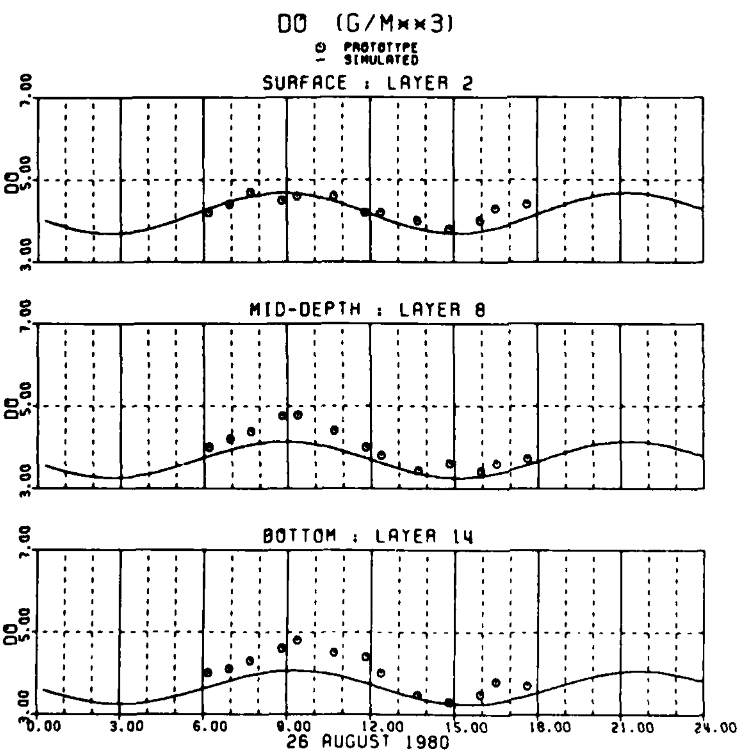

Figure 25. Measured and calculated DO, 26 August 1980

time necessary for equilibration. The initial conditions of the extended simulation were 0.0 ppt salinity, 28.0° C, and a flat water surface.

61. Figures 26 through 28 represent the transient respons of salinity

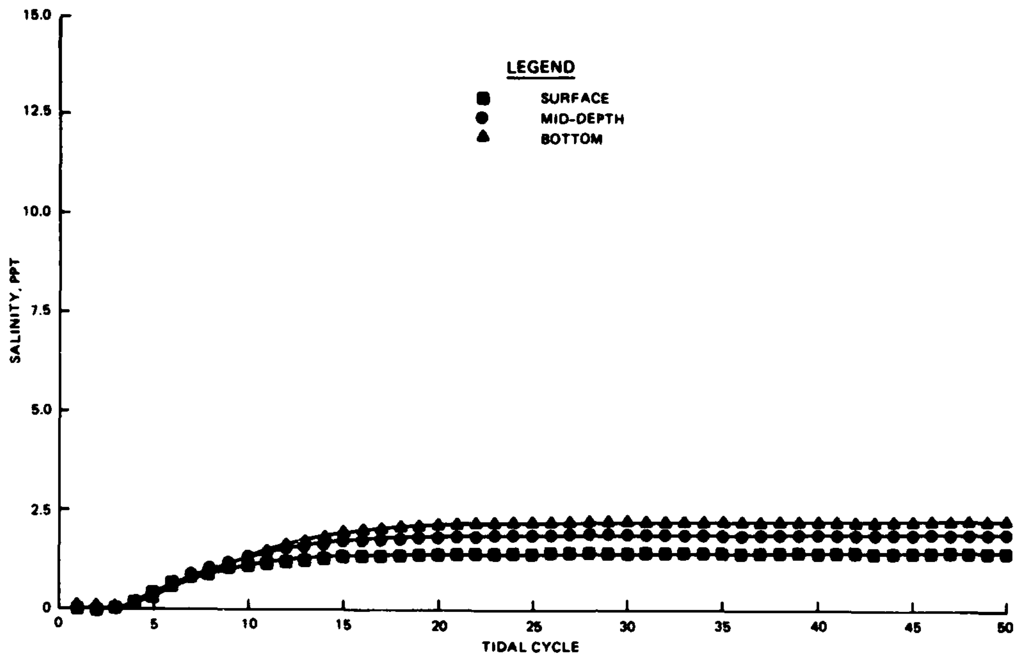

Figure 26. Transient response, simulated tidally averaged salinity, Segment 21

in Segments 21, 27, and 29 at the surface, middepth, and bottom. Equilibrium of salinity was achieved in 10 to 20 tidal cycles. Figures 29 through 31 represent the tidally averaged salinity profile after 1, 25, and 50 tidal cycles. Figures 32 through 34 present the corresponding tidally averaged velocity. For the Savannah River Estuary simulations, a restart file based on 28 days (54 tidal cycles) was used. Test runs were initiated from the restart file, and these ran for 5 days (10 tidal cycles) before comparisons were made.

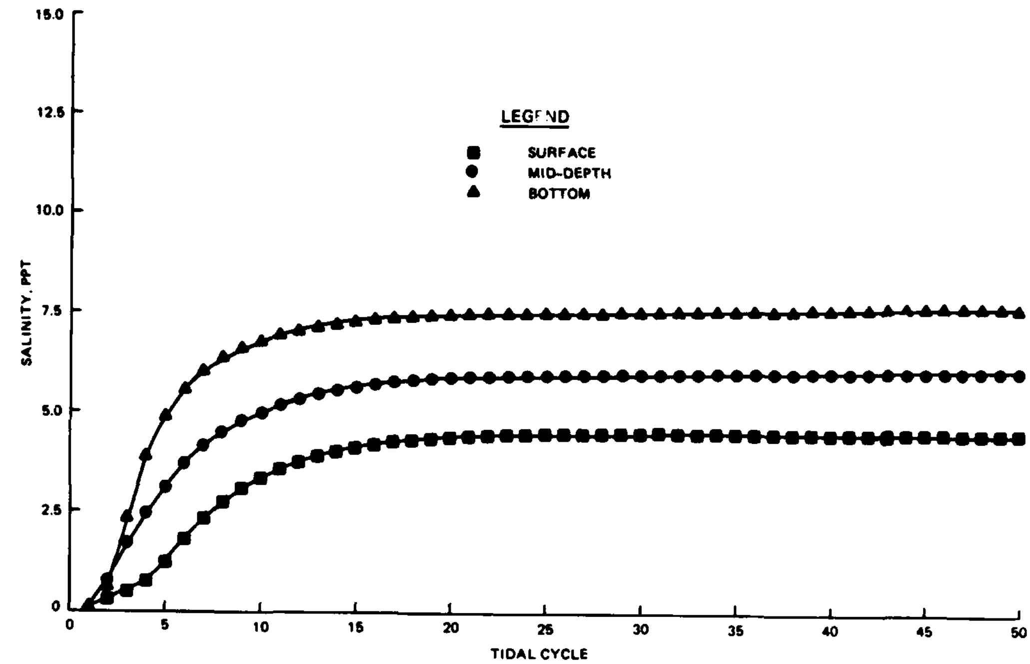

Figure 27. Transient response, simulated tidally averaged salinity, Segment 27

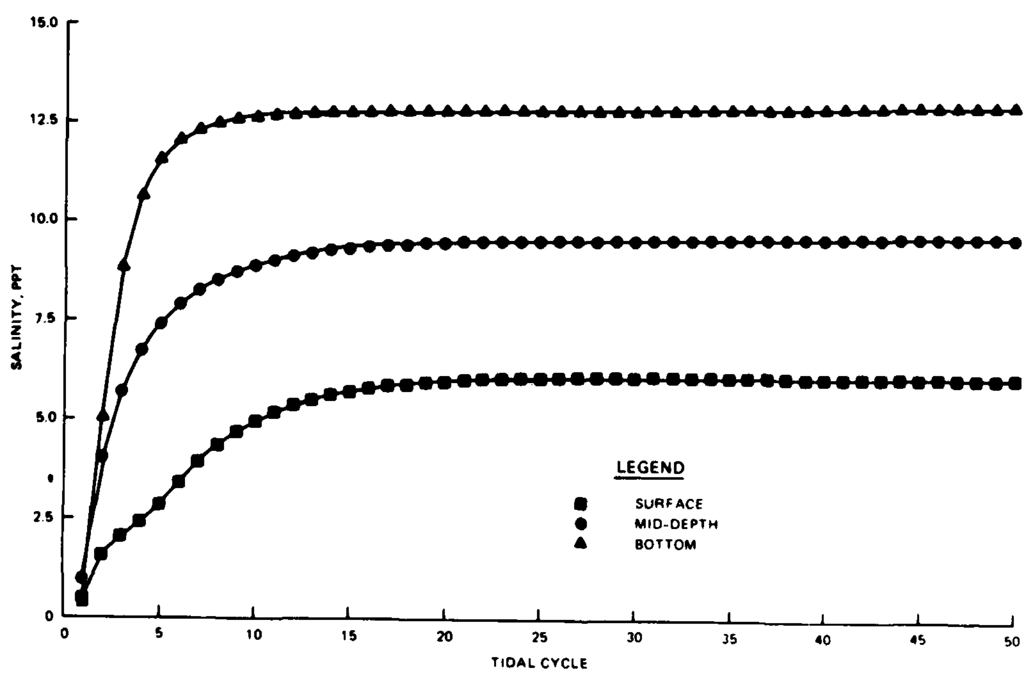

Figure 28. Transient response, simulated tidally averaged salinity, Segment 29

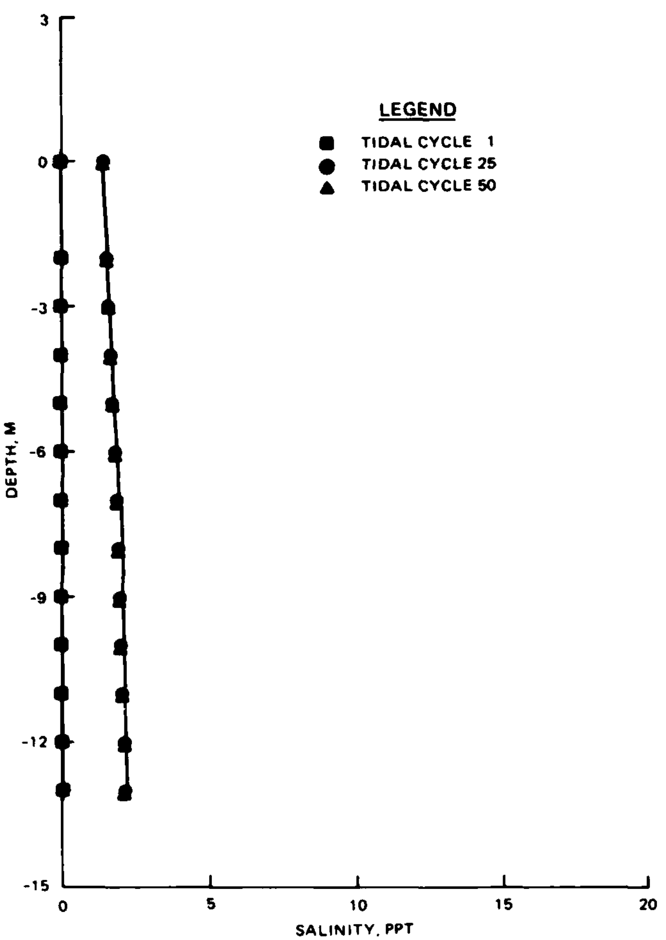

Figure 29. Simulated tidally averaged, vertical salinity profile, Segment 21

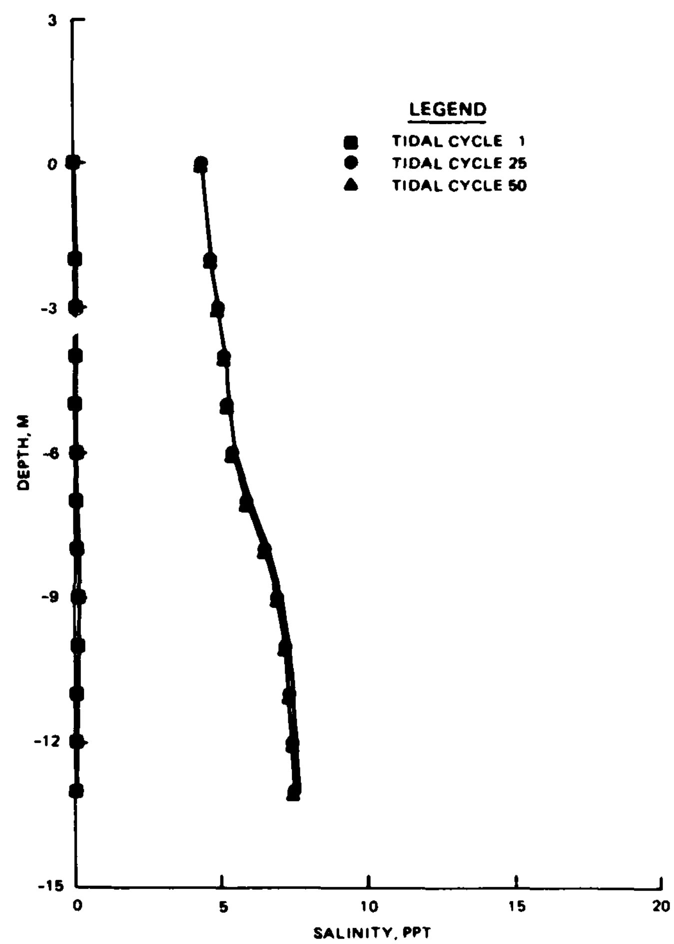

Figure 30. Simulated tidally averaged, vertical salinity profile, Segment 27

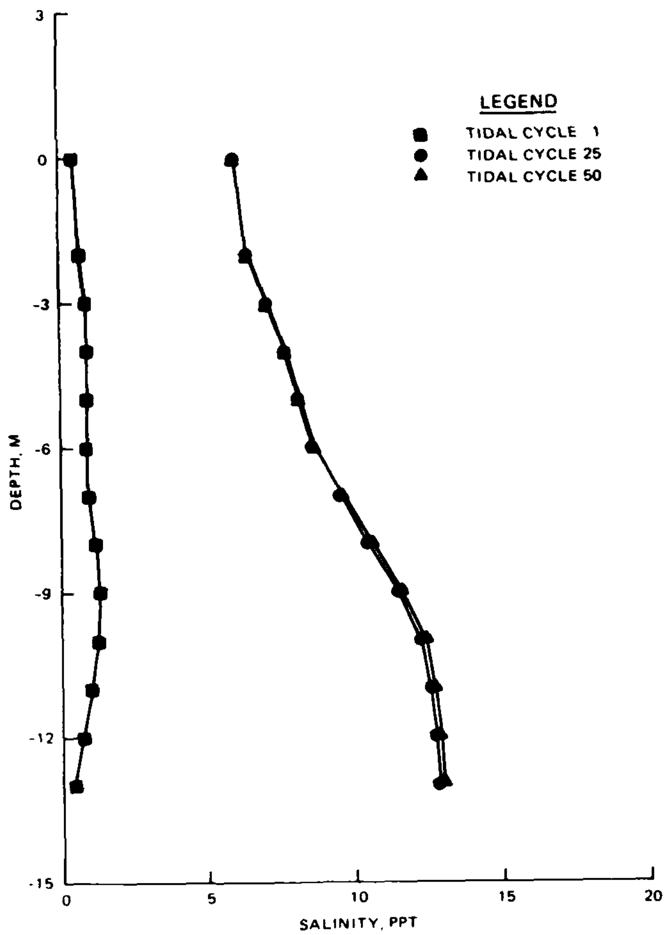

Figure 31. Simulated tidally averaged, vertical salinity profile, Segment 29

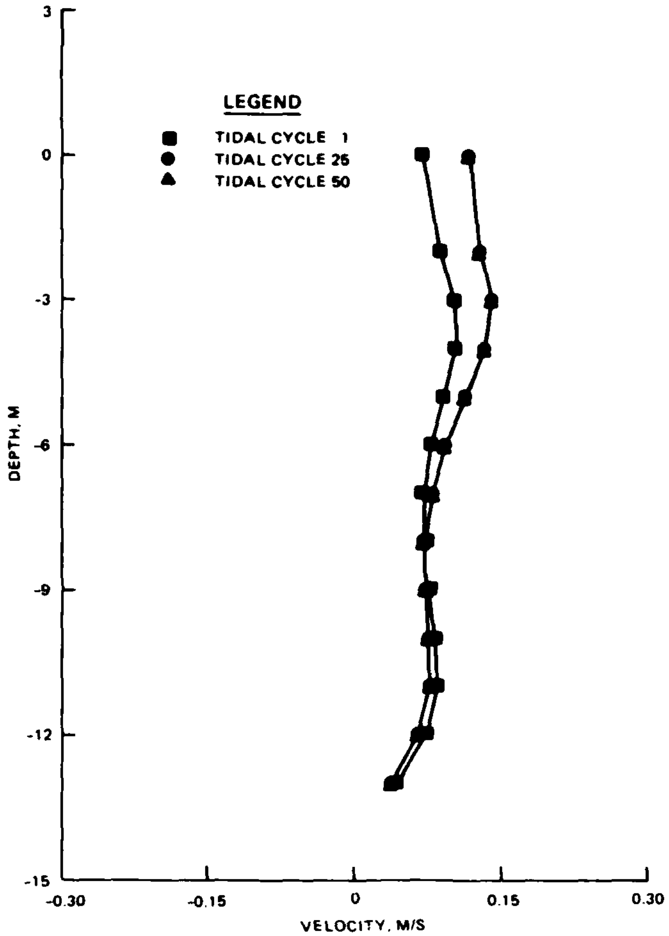

Figure 32. Simulated tidally averaged, vertical velocity profile, Segment 21

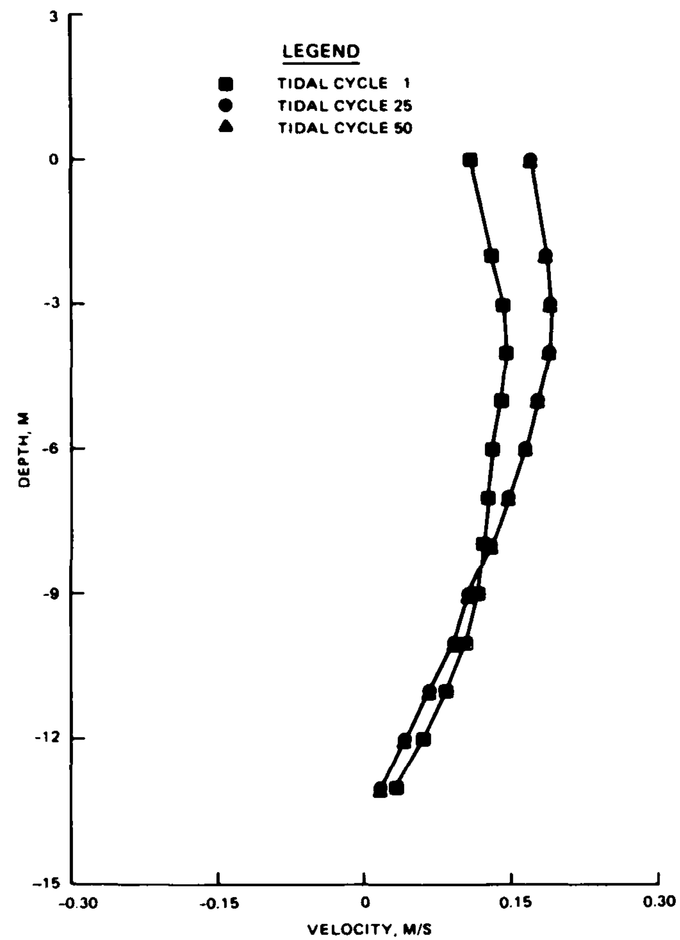

Figure 33. Simulated tidally averaged, vertical velocity profile, Segment 27

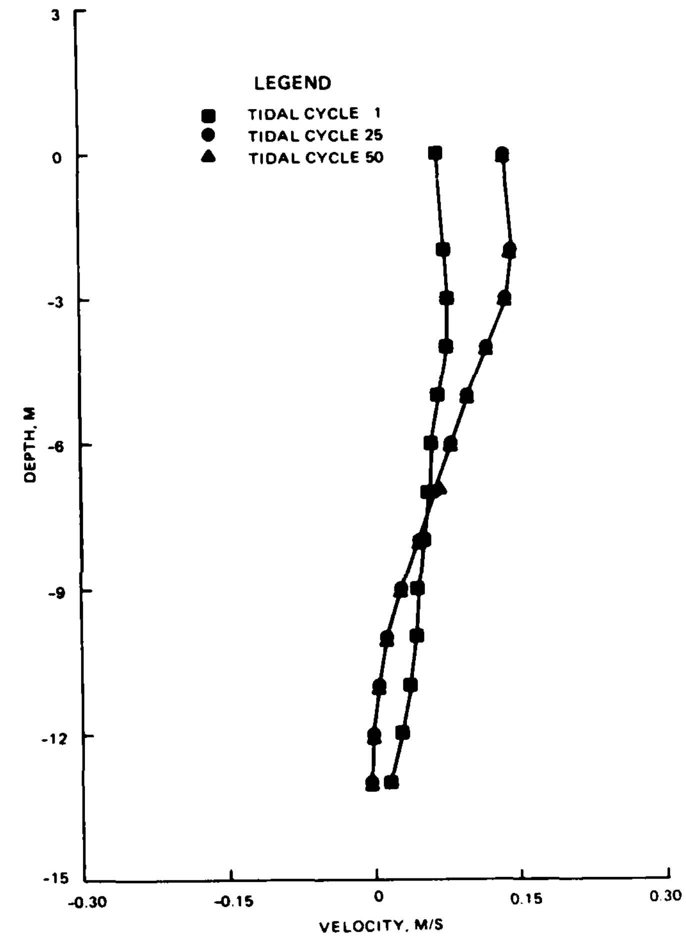

Figure 34. Simulated tidally averaged, vertical velocity profile, Segment 29

PART III: RESULTS

Hydrodynamic Adjustment

Tides and velocities

62. Two results of the simulations were used to achieve hydrodynamic adjustment: spatial and temporal variation of tide height and the pattern of circulation throughout the tidal cycle. The numerical model provided one coefficient, the Chezy coefficient, that had detectable influence on tidal variation and velocity fields and could be varied to achieve hydrodynamic adjustment. The Chezy coefficient relates vertical velocity gradients to bottom and interlayer stresses.

63. Initial simulations revealed that simulated tidal amplitudes were nearly equal to measured (surface elevation recorder at RM 11, Segment 29) and predicted (NOAA Tide Tables (1980)) amplitudes, but that tidal phase lags occurred and increased upestuary (Table 13). The phase errors varied with the Chezy coefficient, but phase errors could not be eliminated by manipulation of the Chezy coefficient alone.

64. Simulated velocities increased with increased values for the Chezy coefficient, but simulated surface velocities were consistently less than those measured. Simulation results also indicated that tidal fluctuations increased in magnitude at the upstream boundary with the increased Chezy coefficient. The upstream boundary at Ebenezer Landing is upestuary of the fall line, and thus the water surface elevation should not tidally fluctuate in the simulations. In order to eliminate simulated tidal fluctuation at the upstream boundary and to minimize tidal phase errors, the coding was modified to make the Chezy coefficient equal to 30 in the navigation channel and sediment basin and 25 in the nondredged channel.

65. The observation that simulated tidal elevations were nearly equivalent to measured values whereas simulated tidal velocities were less than measured values implied that the system geometry was in error. The detailed "Savannah Harbor, Georgia, Annual Survey" (SAS 1981) and the detailed "Navigation Charts, Savannah River, Georgia and South Carolina" (SAS 1980) that were used to specify geometry for Branches 1 and 3 were considered adequate. However, the Nautical Chart 11514 (NOAA 1978) that was used to specify Branch 2 geometry contained little detail for the non-navigable channel. The influence

Table 13

Comparison of Simulated and Predicted* Tidal Range and Phase, 12 August 1980

			Tidal Range Error, m** Chezy			Tidal Phase Error, min** Chezy					
						30		40		60	
	RM	Segment	30	40	60	Flood	Ebb	Flood	Ebb	Flood	Ebb
Savannah	14.4	27	0.3	0.1	0.2	-6	-3	-14	-12	-30	-22
Port Wentworth	21.0	22	0.1	0.0	0.0	-27	-12	-34	-30	-36	-48
ACL RR Bridge	27.4	16	0.0	-0.2	-0.2	-60	-63	-78	-81	-94	-102

* Predicted based on NOAA Tide Tables (1980).
** Error defined as predicted minus simulated.

of underestimating the storage of Branch 2 was examined by systematically increasing the section widths and noting the resulting ebb velocities in Front River. Increasing Branch 2 storage by 20 percent increased ebb velocities by less than 4 percent. Because of the apparent insensitivity of resulting ebb velocities to moderate increases in storage, the estuarine geometry that could be abstracted from the harbor survey, navigation, and nautical charts (SAS 1980 and 1981; NOAA 1977 and 1978) was used without modification. Subsequent investigations revealed that extensive storage occurs through overbank flooding. Overbank flooding was not included in the model.

66. Simulated and measured tidal elevations at RM 11 (Segment 29) are displayed in Figure 35. Simulated and measured surface, middepths, and bottom velocities at RM 11.4 (Segment 29) and RM 17.2 (Segment 24) are illustrated in Figures 36 through 41. Examination of Figure 35 reveals that tidal amplitude and phase were reproduced in downestuary segments. However, as discussed previously, tidal phase errors occurred at upestuary locations (Table 13).

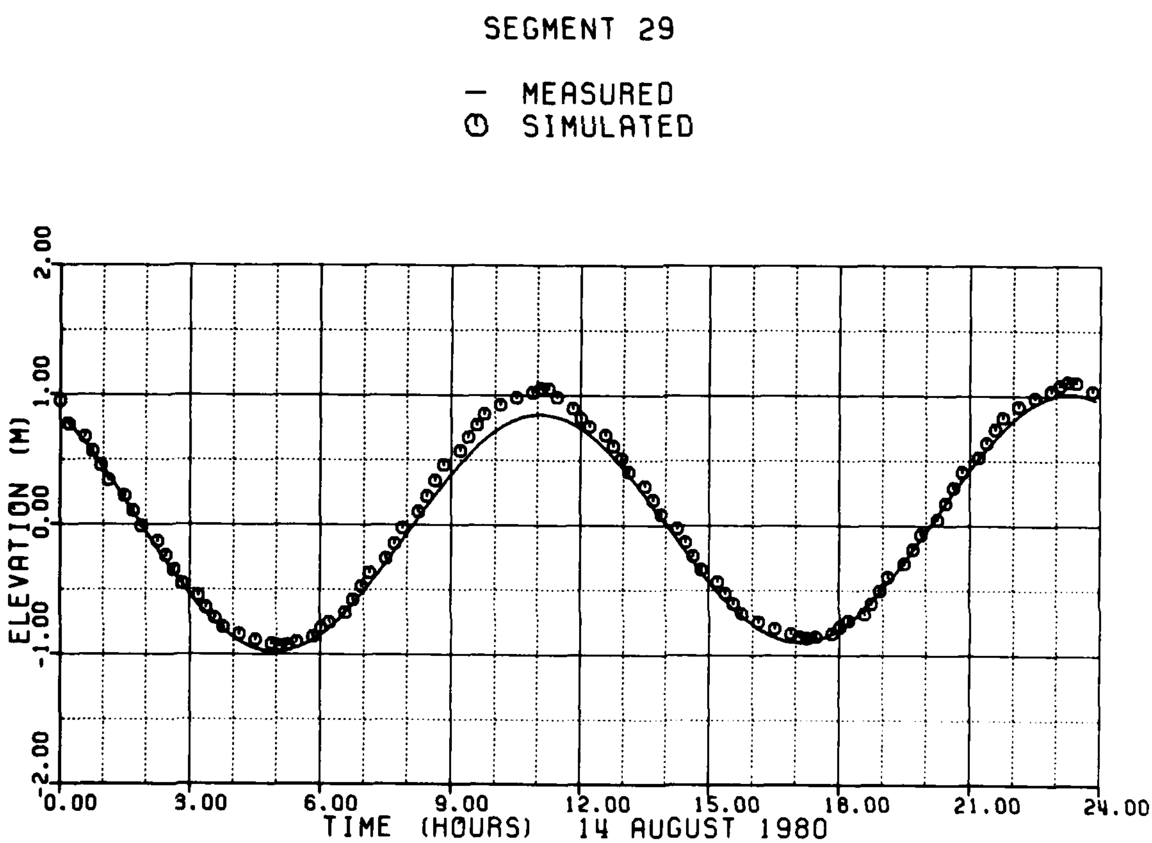

Figure 35. Simulated and measured tidal elevations at Segment 29

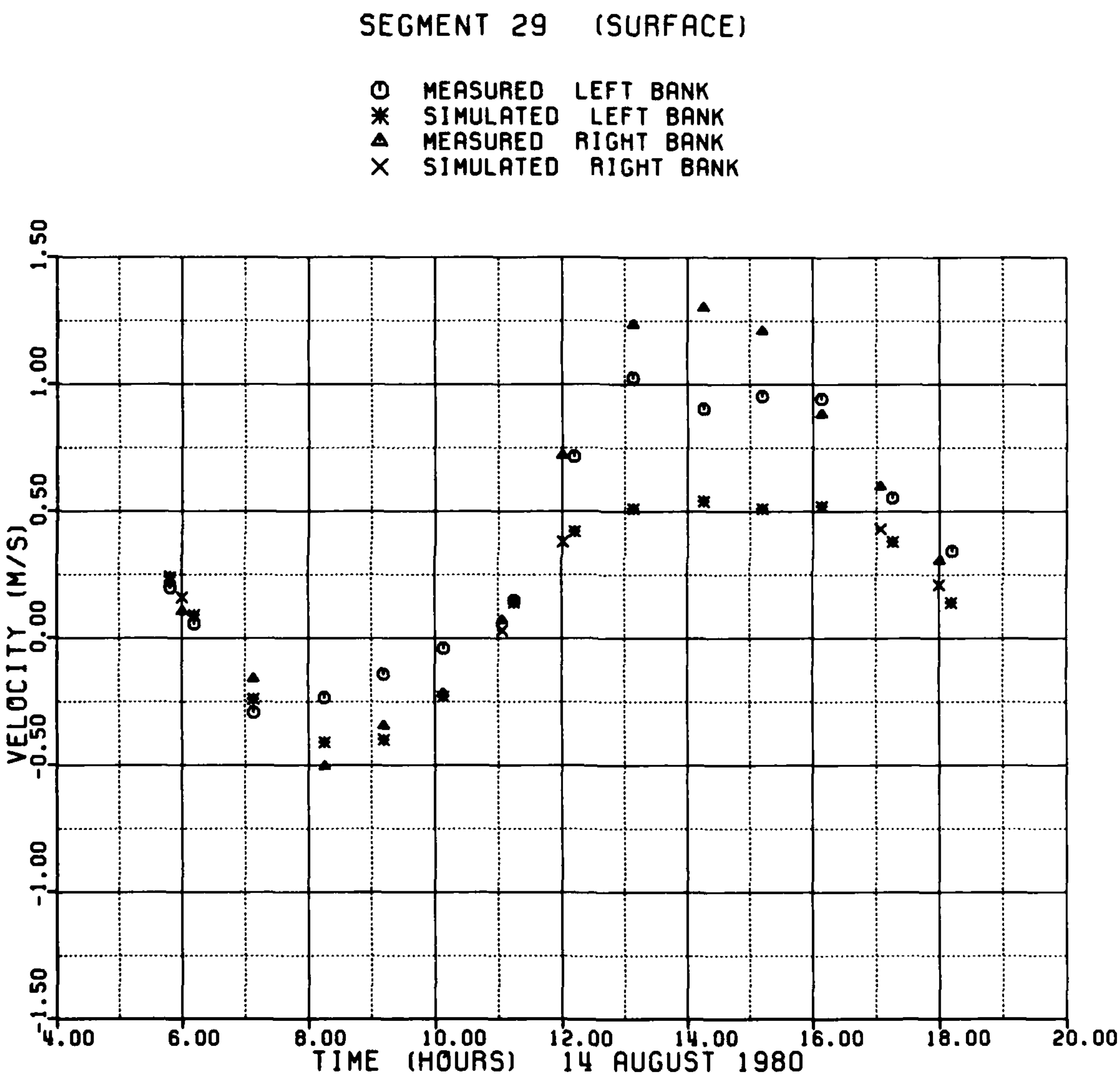

Figure 36. Simulated and measured surface velocities at Segment 29

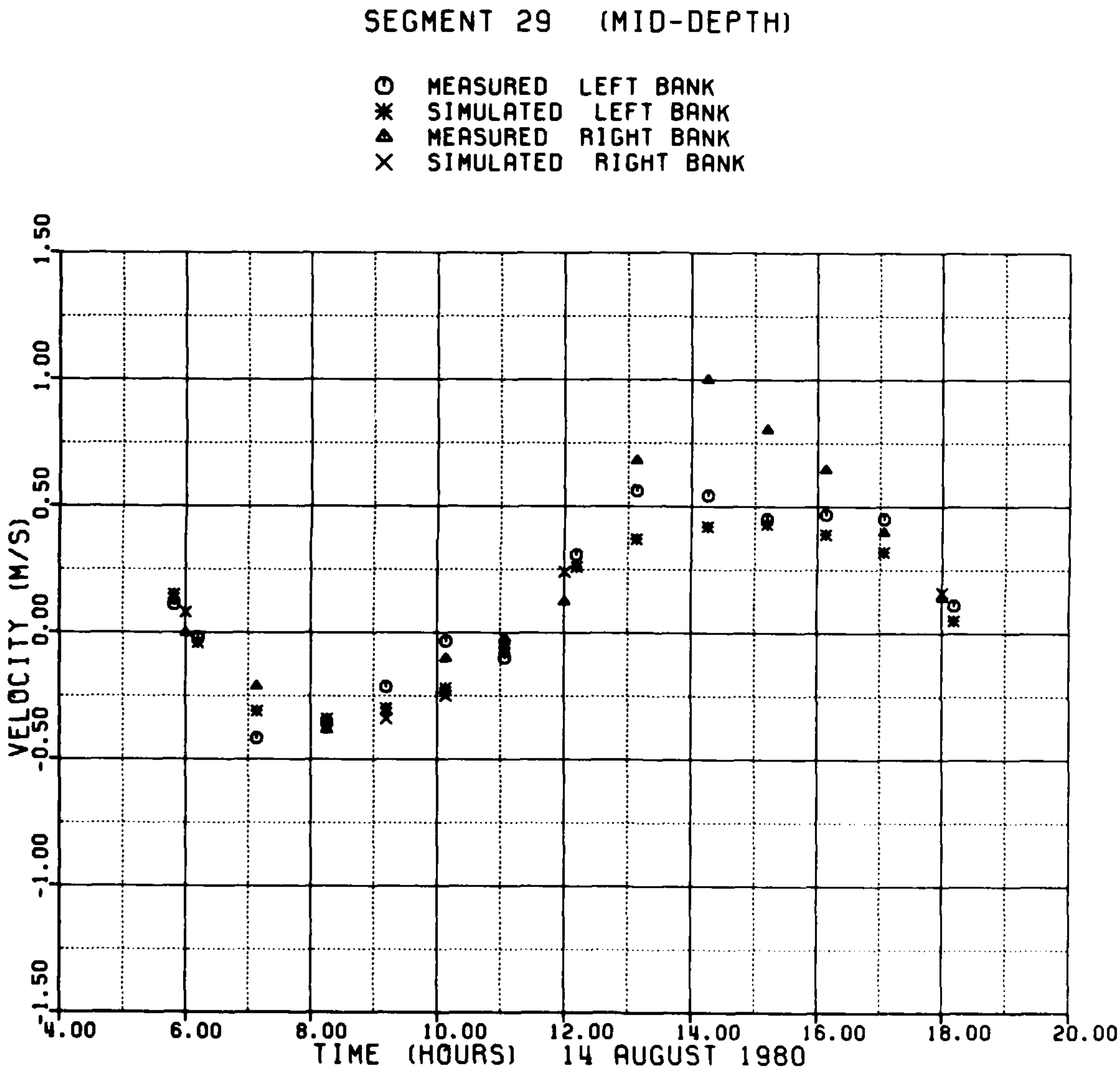

Figure 37. Simulated and measured middepth velocities at Segment 29

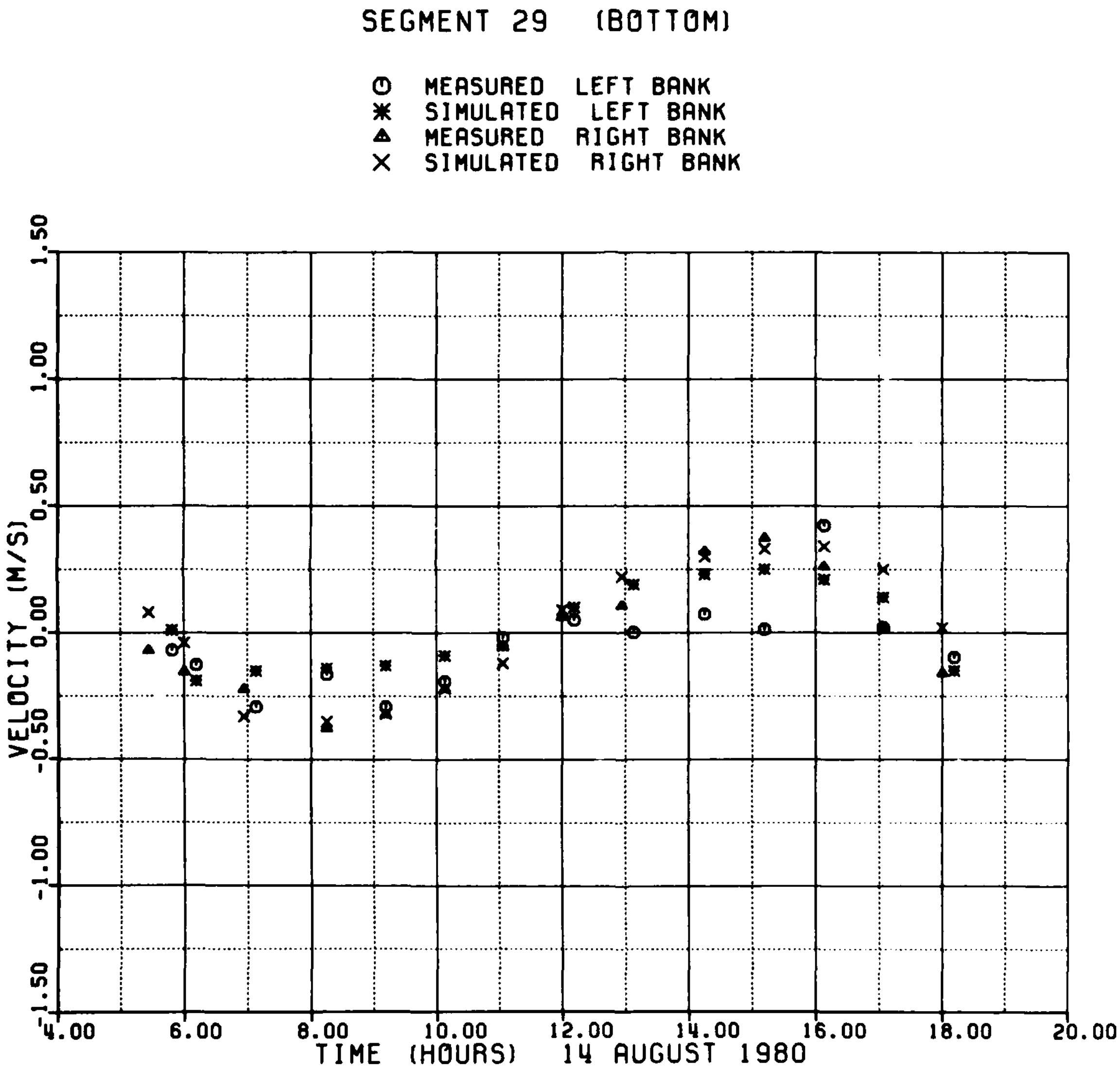

Figure 38. Simulated and measured bottom velocities at Segment 29

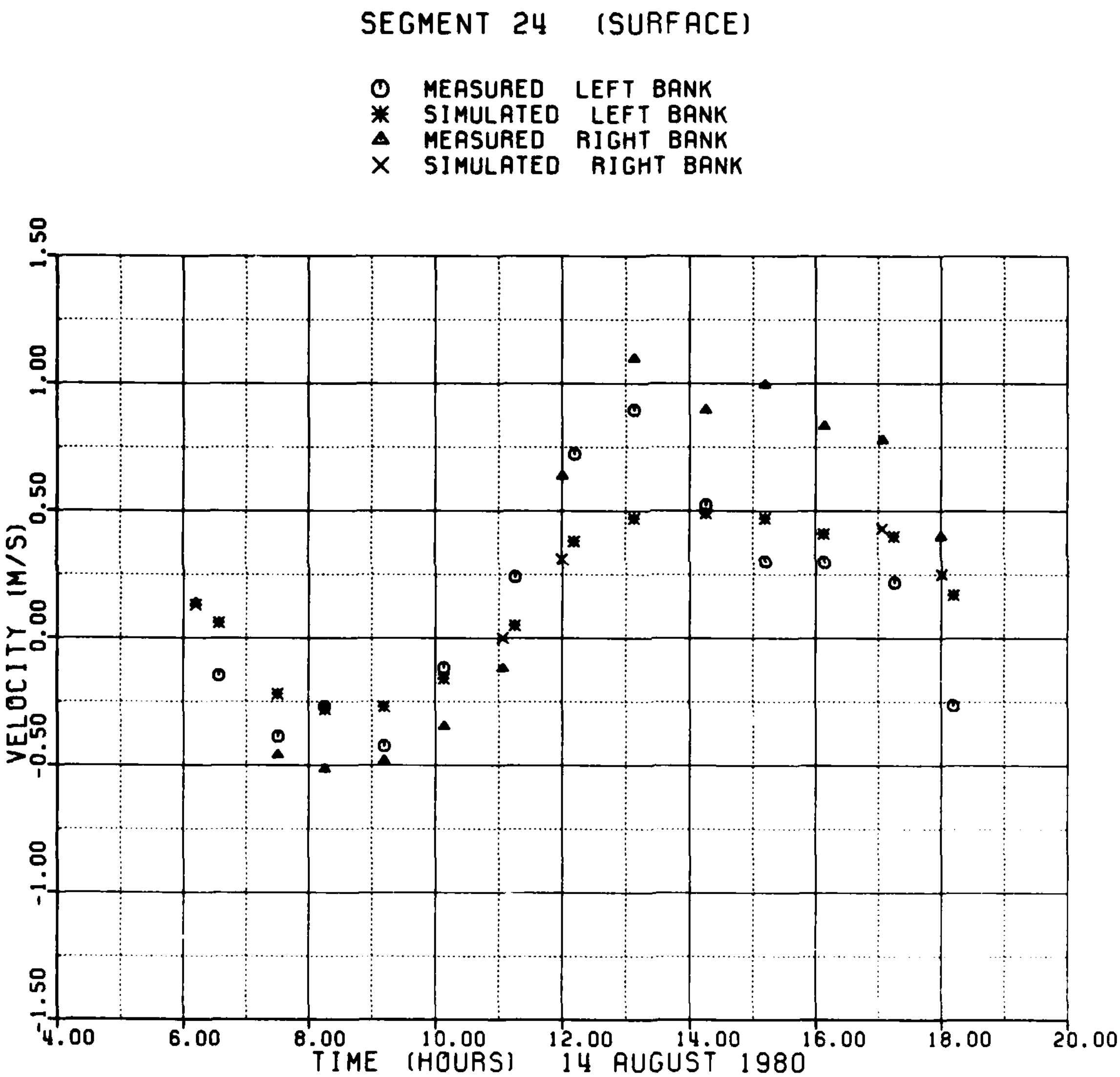

Figure 39. Simulated and measured surface velocities at Segment 24

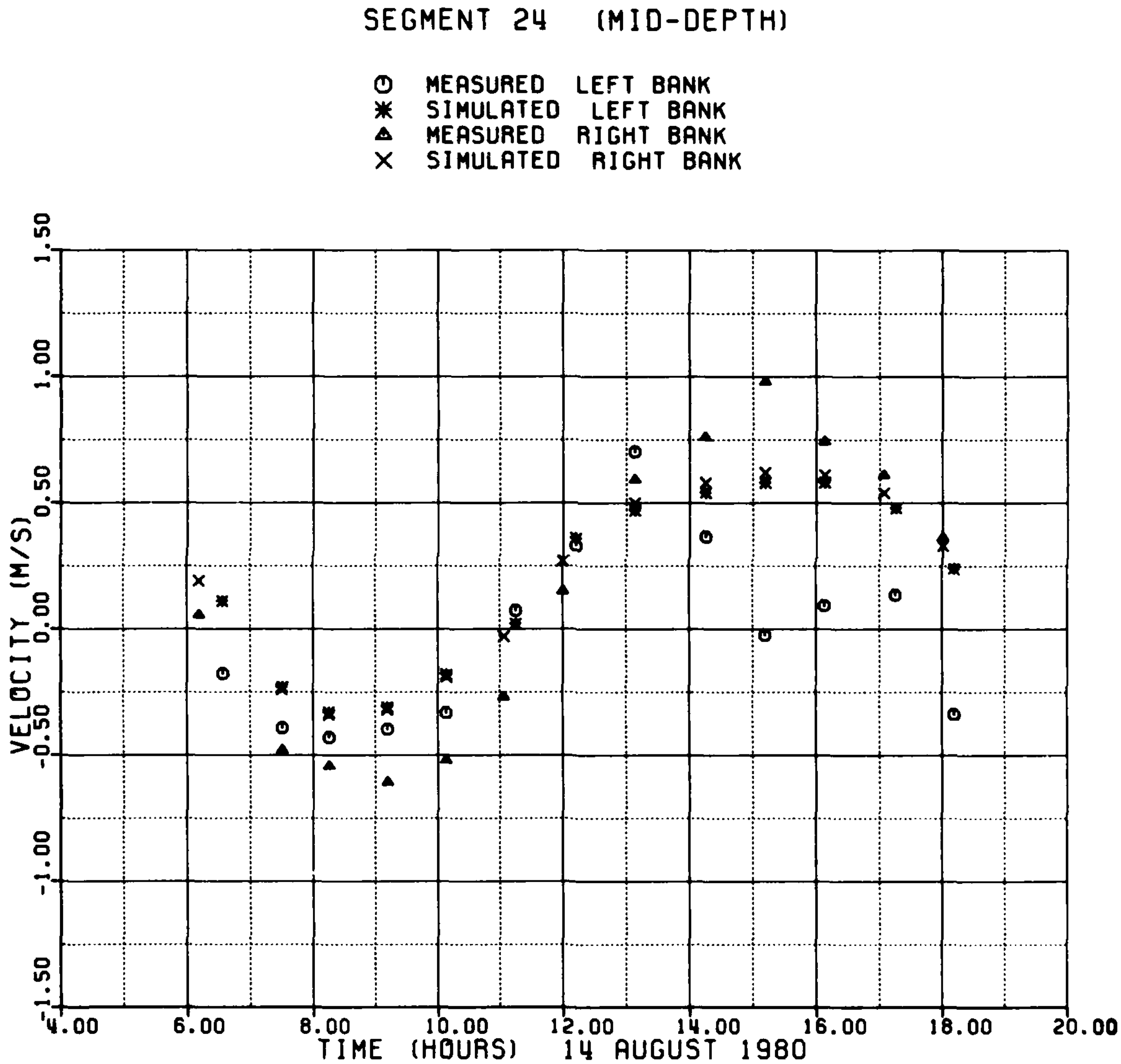

Figure 40. Simulated and measured middepth velocities at Segment 24

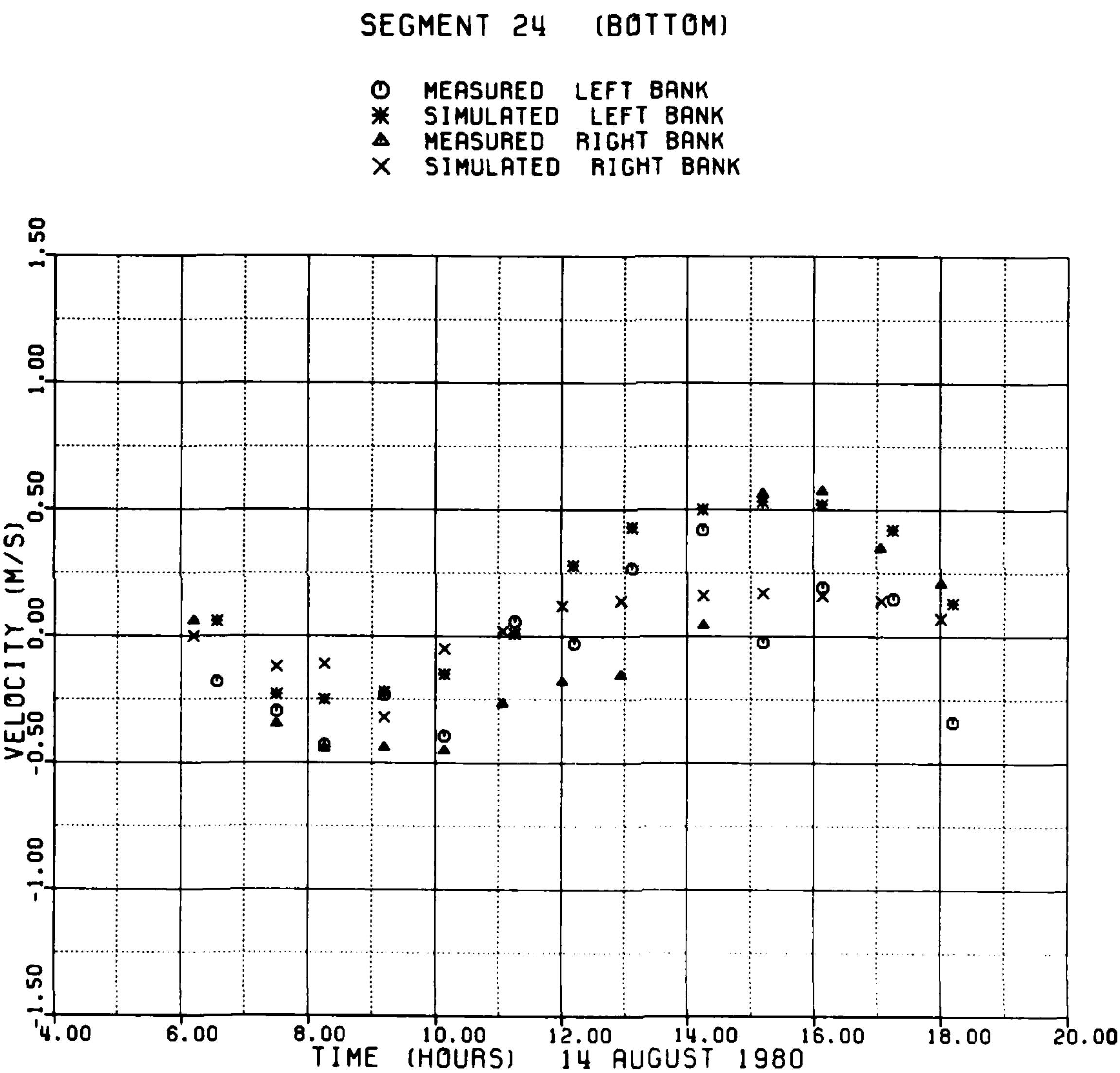

Figure 41. Simulated and measured bottom velocities at Segment 24

Comparison of simulated and measured velocities indicates greater differences at Segment 29 than at Segment 24, greater differences during ebb (velocities positive) than during flood, and greater differences at the surface than at the bottom.

67. The distinction between right and left bank simulated velocities in Figures 36 through 41 was due to the fact that simulated and measured velocities were matched with respect to time and depth of measurement. The time required to sample both the left and right bank was approximately 30 min; the comparison of measured and simulated velocities corresponds to within 3 min, with the result that left and right bank comparisons may differ by 30 min. The sampling was conducted adjacent to the navigation channel, and the measured depths differed on either side of the channel; therefore, bottom and middepth measurements differed in elevation and frequently corresponded to different model layers.

68. Variations between observed and predicted tidal velocities and phases were attributed in part to inaccuracies in the model geometry. Two observations need to be considered in future estuarine applications. First, the navigation charts used for specification of the system geometry typically recorded depths no shallower than MLW. The specification of segment widths at elevations no higher than MLW is duplicated by the computer code GEDA at higher elevations. This results in an underestimate of cross-sectional areas during the tidal cycle at elevations greater than MLW. Topographic maps did not provide the resolution required for the Savannah River application. Second, extensive areas of the Savannah River Estuary are subject to overbank flooding during the tidal cycle, and nautical charts may be in error for non-navigable streams.* These observations suggest that recent detailed topographic surveys be used or that personal observation be employed to define the areal extent and depth of overbank flooding in order to accurately reproduce the systems geometry.

Salinity

69. Figure 42 illustrates a comparison of simulated and measured salinity profiles for Segments 24, 27, and 29 for four sampling dates. The measured salinities were abstracted from the center-line water quality survey

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* Personal Communication, 9 August 1985, Billy H. Johnson, Research Hydraulic Engineer, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

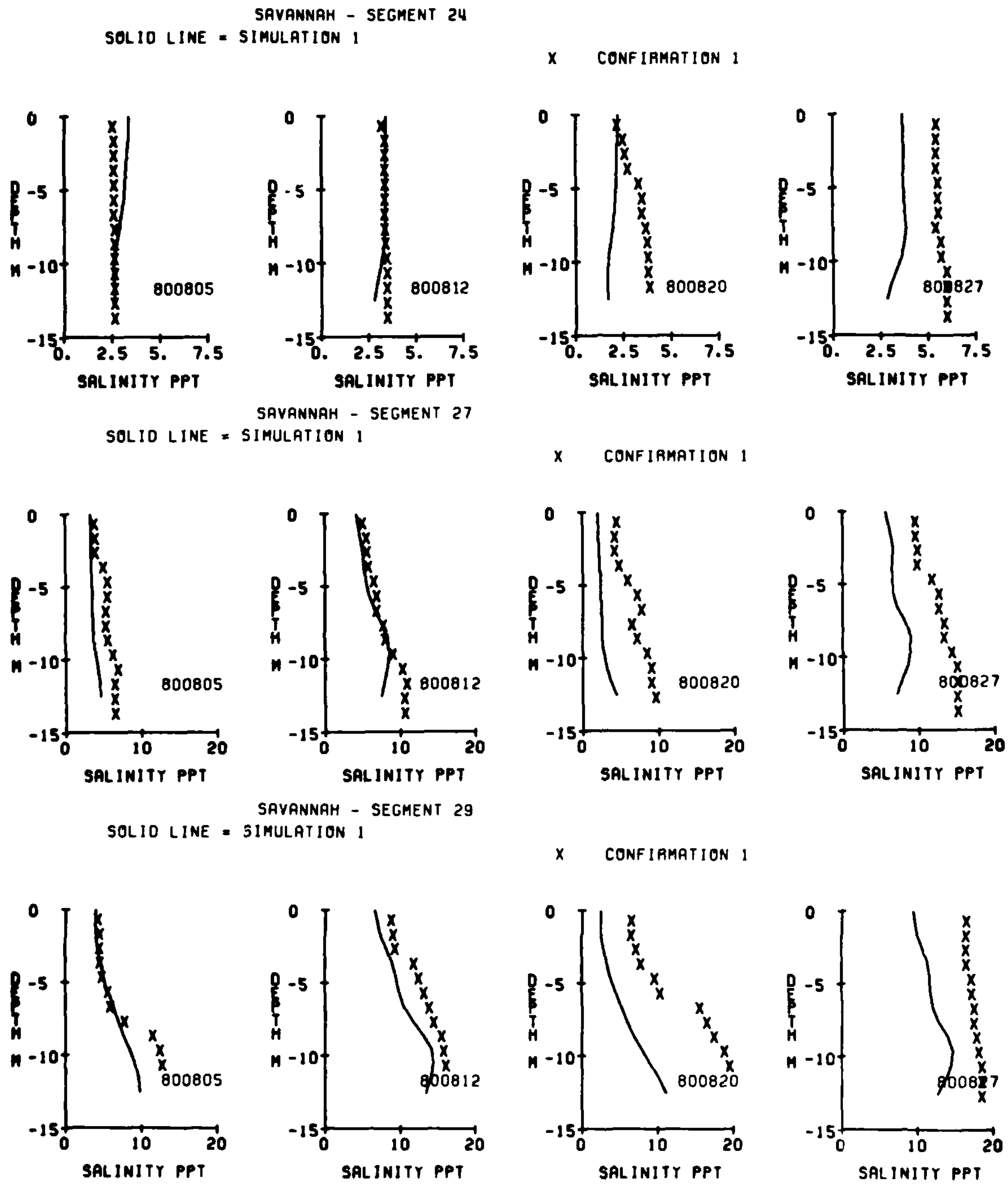

Figure 42. Simulated and measured salinities at Segments 24, 27, and 29

(Pennington and Bond 1981). Figures 43 through 46 represent snapshots of the simulated velocity structure and water surface elevation corresponding to the time of profile measurement. The simulated salinities closely approximate the measured values on August 5 and 12 but deviate on August 20 and 27. Adjustment of the horizontal dispersion coefficient between 1 and 10 m^2/sec had no detectable effect on salinity concentrations.

70. Two possible reasons are postulated to account for these apparent deviations. The first is that the center-line surveys required 4 hr for their completion. The simulation snapshots for profile comparison were made at the arithmetic average of sample collection times resulting in possible deviations of up to 2 hr between simulated and measured values. The Savannah River Estuary is quite dynamic with observed salinity variations at some stations exceeding 5 ppt over a 2-hr period. The second reason is the possible existence of errors in the advective transport because of unaccounted overbank storage or discrepancies in geometry. The discrepancy between measured and simulated velocities supports this hypothesis.

Water Quality

71. The model test program consisted of two levels of constituent formulations. The first level consisted of only DO and BOD relationships, whereas the second included the addition of the nutrients nitrogen and phosphorus and the biological component algae. Experiments were conducted using the DO-BOD formulation to demonstrate the utility of CE-QUAL-W2 for investigating changes in upstream regulation and evaluating permit applications. Sensitivity analyses were conducted using both levels of kinetic formulations in order to investigate the importance of tidal boundary constituent concentrations.

Formulation 1: DO-BOD

72. Calibration. Examination of Figures 47 through 49 reveals that simulated and measured profiles of temperature, BOD, and DO are nearly equivalent. The results were quite good considering the difficulty in specifying head boundary constituent profiles.

73. Head boundary sensitivity experiment. The head boundary constituent profiles were based on the 1980 survey results. A factorial sensitivity experiment was conducted in order to evaluate the effects of imprecise

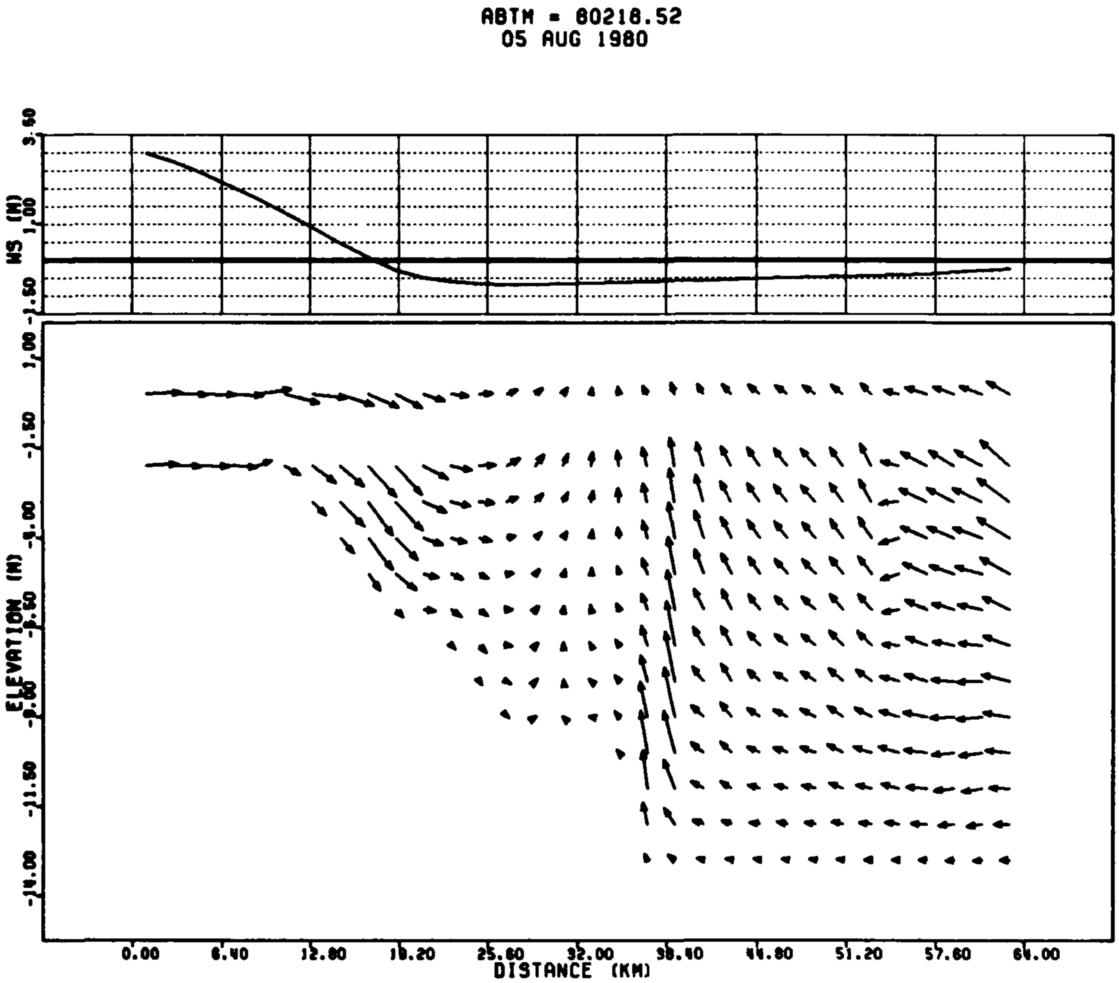

Figure 43. Simulated velocity structure and water surface elevation, 12:30 PM, 5 August 1980

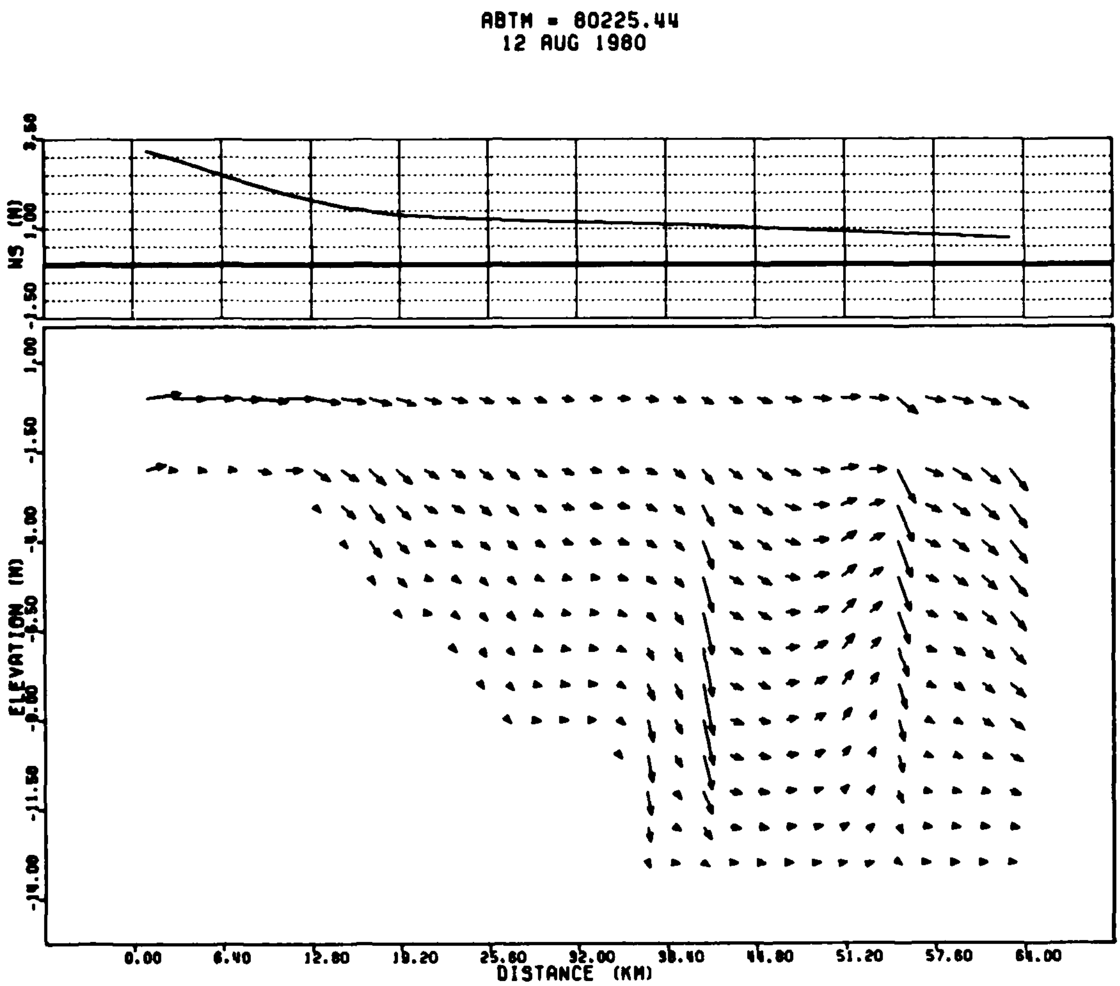

Figure 44. Simulated velocity structure and water surface elevation, 10:30 AM, 12 August 1980

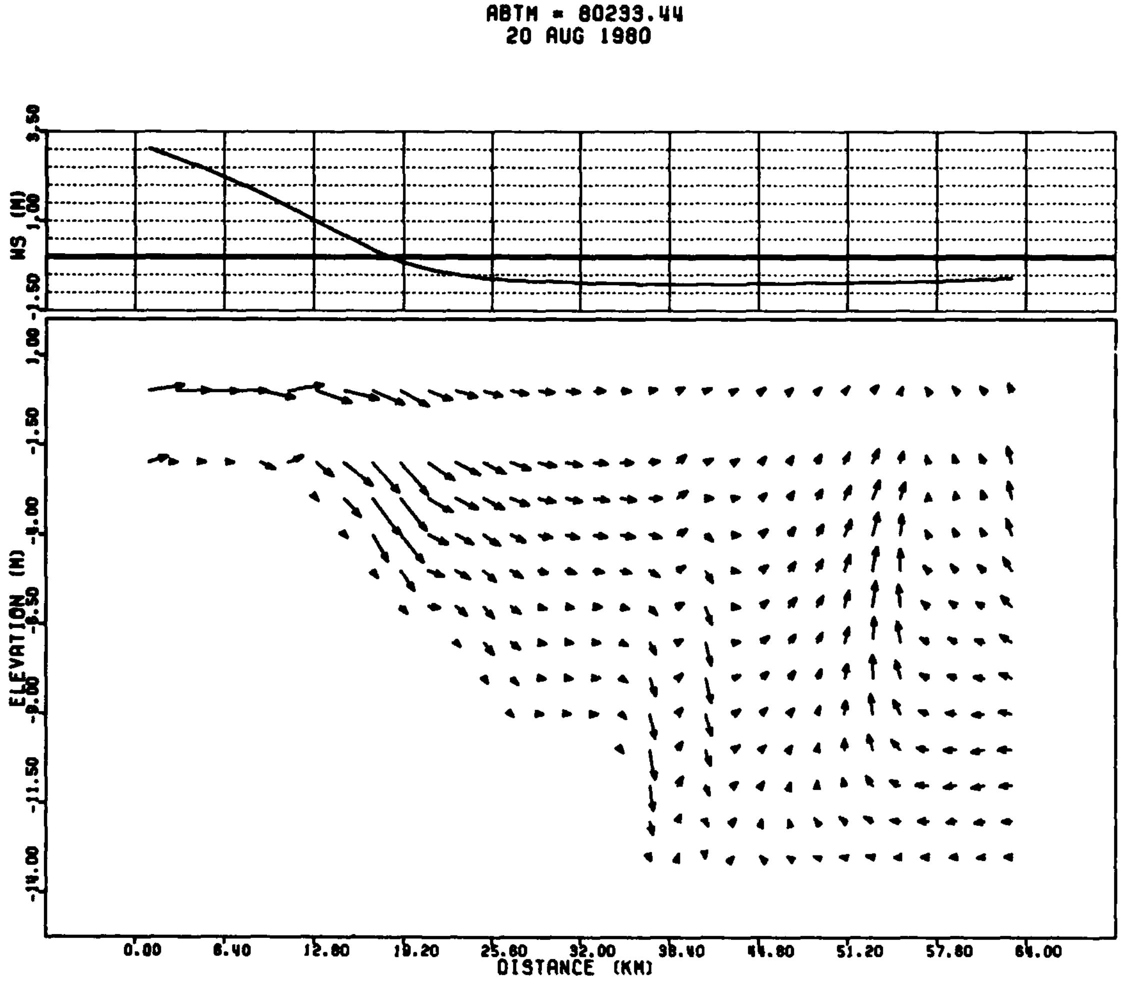

Figure 45. Simulated velocity structure and water surface elevation, 10:30 AM, 20 August 1980

ABTM = 80240.43
27 AUG 1980

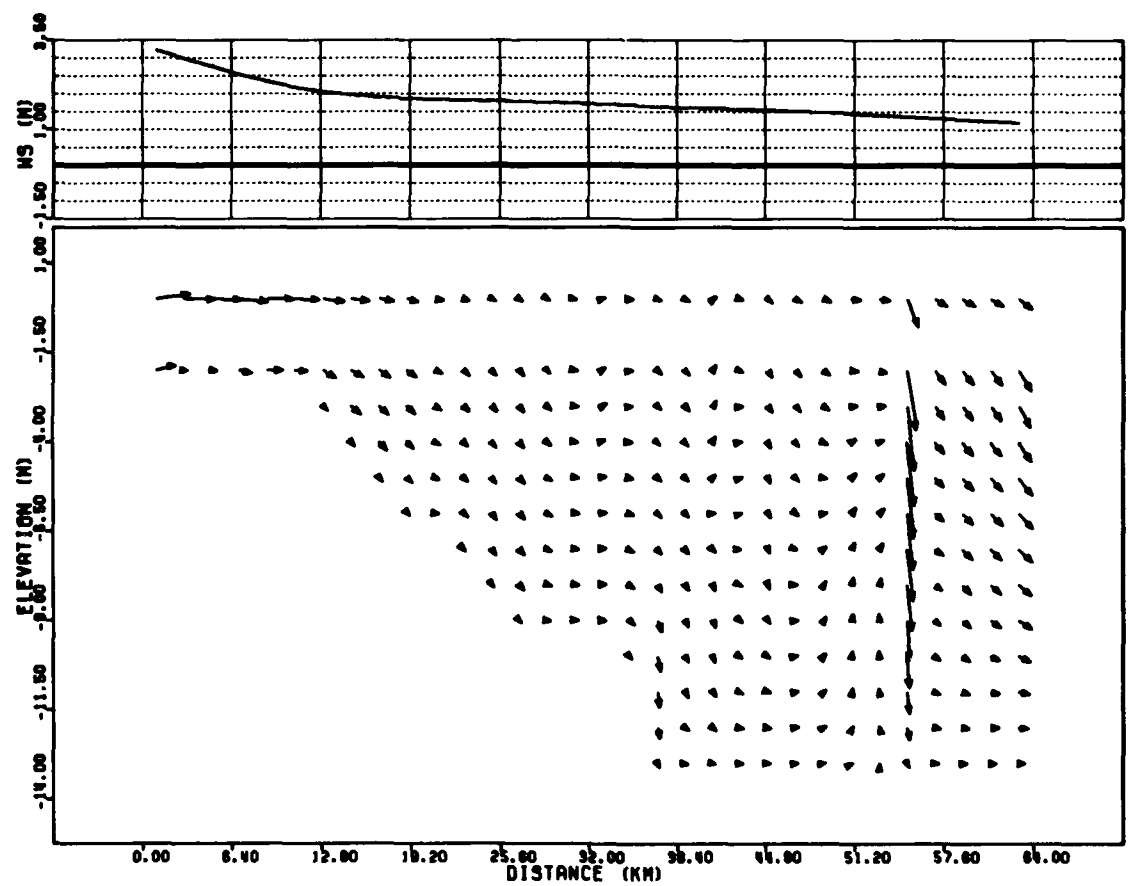

Figure 46. Simulated velocity structure and water surface elevation, 10:20 AM, 27 August 1980

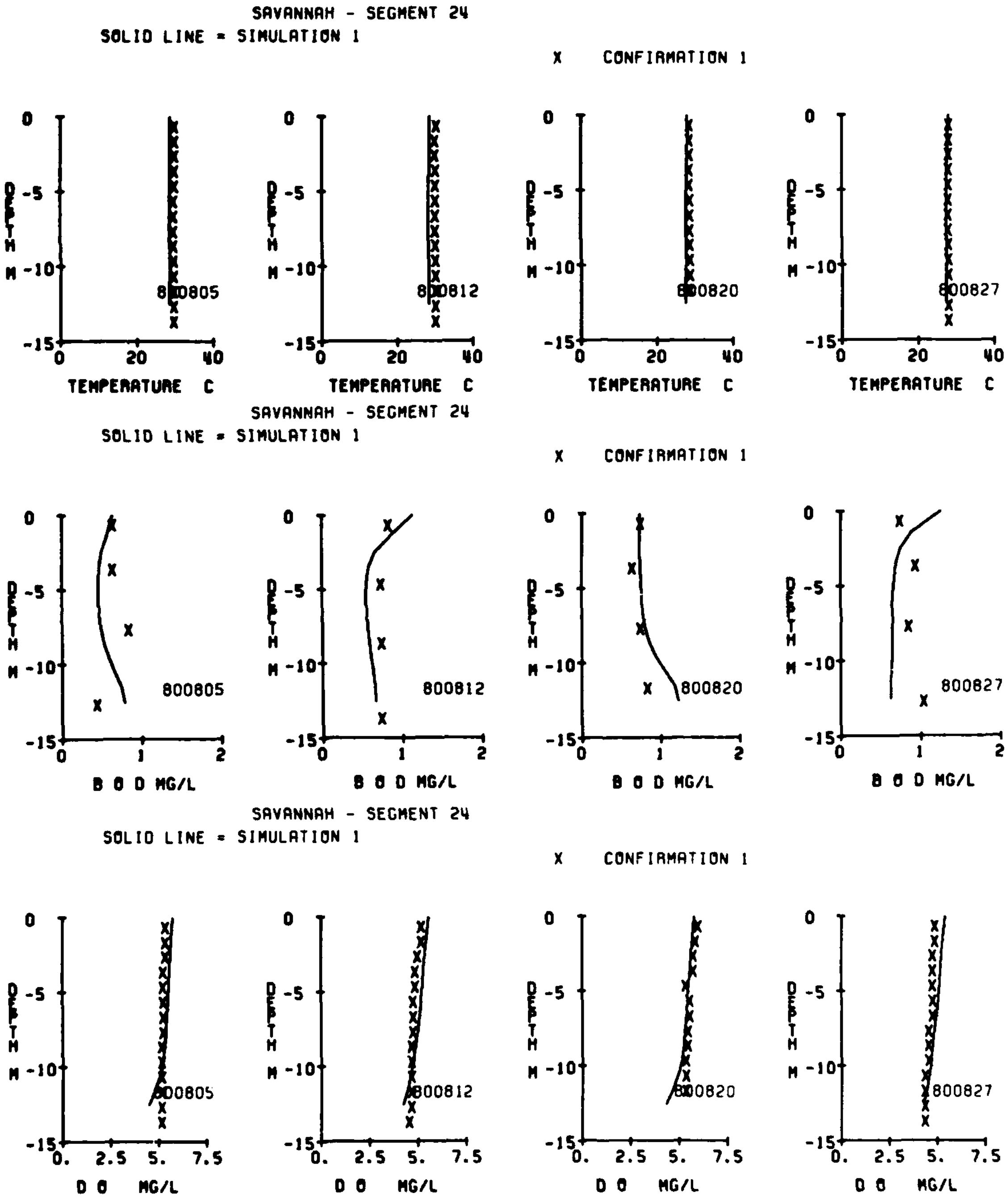

Figure 47. Simulated and measured temperature, BOD, and DO at Segment 24

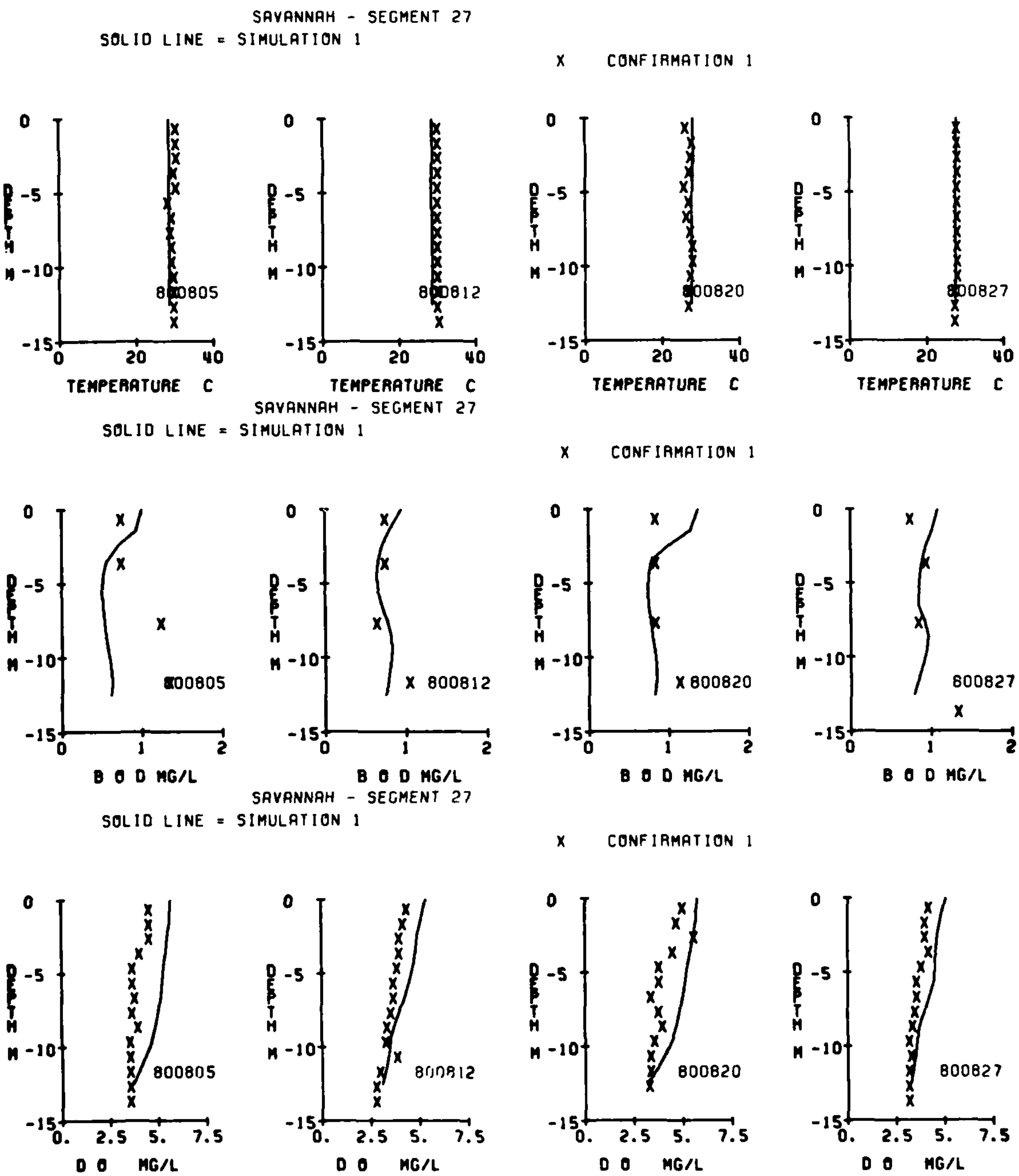

Figure 48. Simulated and measured temperature, BOD, and DO at Segment 27

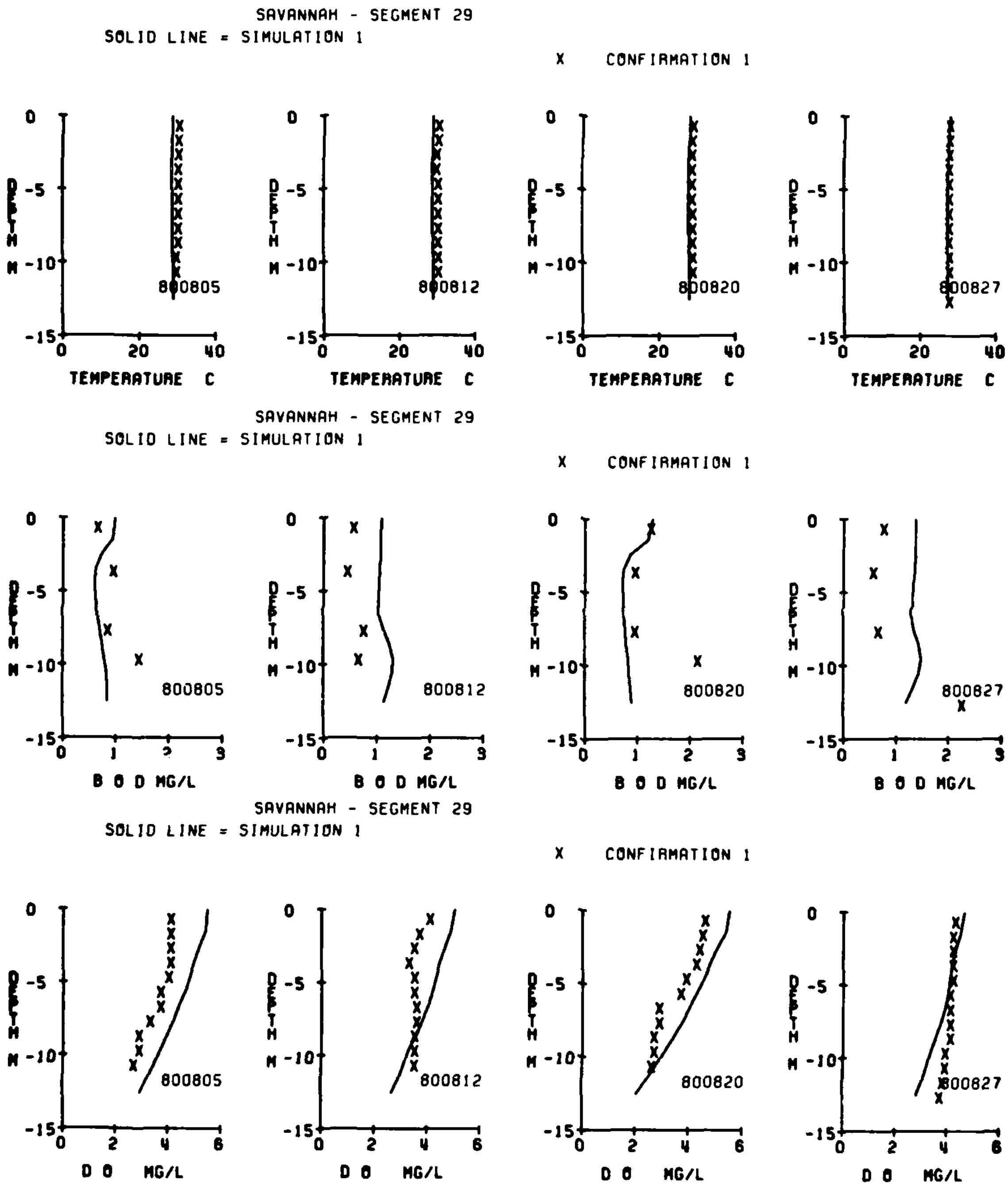

Figure 49. Simulated and measured temperature, BOD, and DO at Segment 29

specification of DO and BOD head boundary concentrations on the simulated tidally averaged DO concentration of the whole modeled system.

74. The results of the experiment are tabulated in Table 14. Examination of Table 14 reveals no interaction between head boundary concentrations of DO and BOD using the response variable of tidally averaged DO. Increasing the head boundary BOD concentration 100 percent decreased the tidally averaged DO concentration 1 percent; decreasing the head boundary DO concentration 50 percent decreased the tidally averaged DO concentration 10 percent. Experiments discussed in the next section of this report revealed that a 25-percent decrease in freshwater flow and a 50-percent increase in BOD loads had minor effects on downstream DO and concentrations. The results of the sensitivity experiments coupled with the results of the decreased flow and increased BOD waste load experiments imply that significant errors were not introduced by not modifying the head boundary concentrations of DO and BOD.

75. Decreased flows and increased waste loads. Figure 50 displays contour plots of tidally averaged DO concentrations under four simulated experimental conditions: (a) minimum release of 173 m^3/sec (6,100 cfs) from New Savannah Bluff Dam, (b) 25-percent decrease in freshwater flow, (c) 50-percent increase in waste loads, and (d) a combination of a 25-percent decrease in freshwater flow and a 50-percent increase in waste loads. A 50-percent increase in waste loads was simulated by injecting 126 g/sec BOD between RM 21.1 (the US Highway Houlihan Bridge) and RM 24.5. Examination of Figure 50 reveals a DO minimum near the downstream boundary under all four simulated experimental conditions. Decreased flows resulted in a slight upstream migration of the DO contours, and increased waste discharges resulted in a slight decrease of the DO in the bottom waters near Segment 20. A combination of decreased flows and increased waste loads resulted in conditions similar to decreased flows alone. The results of the experiment suggest that the DO concentration of the Savannah River is rather insensitive to moderate decreases in flow or increases in waste discharge.

Formulation 2: DO, algae, and nutrients

76. Formulation 2 was an expansion of Formulation 1 that included algae (constituent 7), detritus (constituent 8), phosphorus (constituent 9), ammonia (constituent 10), and nitrite + nitrate (constituent 11). The objective of the formulation was to evaluate the relative model sensitivity of head boundary algal concentrations in comparison with the sensitivity of the maximum

Table 14

Relationship of Tidally Averaged DO Concentration to Head Boundary Profile Concentrations of DO and BOD Demand

Head Boundary Concentrations*		Tidally Averaged DO Concentration, g/m^3
DO	BOD	
0.5	0.5	5.5
	1.0	5.5
	2.0	5.4
1.0	0.5	6.1
	1.0	6.1
	2.0	6.0
2.0	0.5	7.3
	1.0	7.3
	2.0	7.2

* DO and BOD head boundary profile concentration expressed as a multiple of measured concentrations.

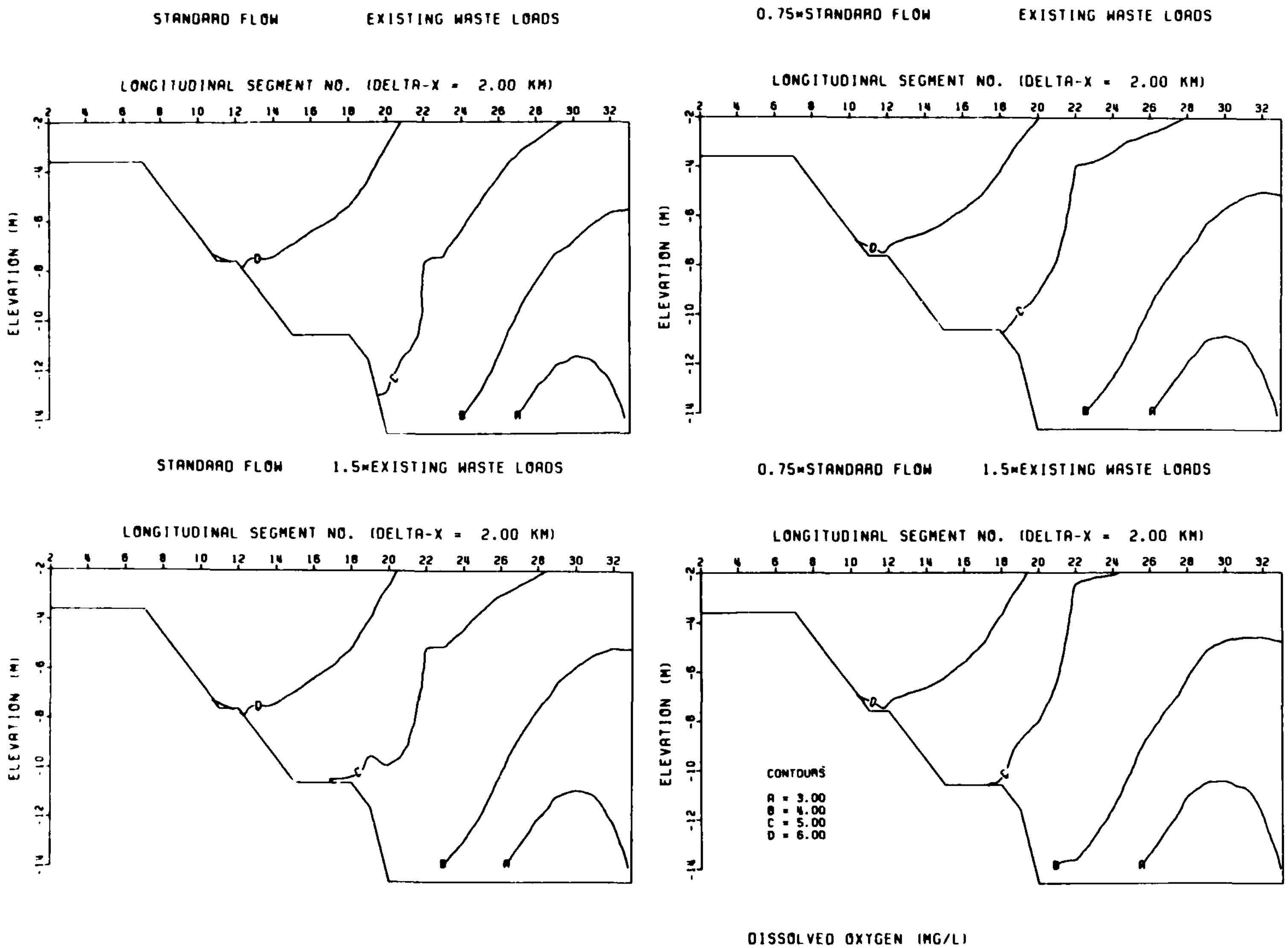

Figure 50. Simulated tidally averaged DO profiles

algal growth rate. Each measured nutrient was assumed to be in a form available to the algae and consistent with model formulations. Reaction rate coefficients were selected equal to the midrange values tabulated in the report "CE-QUAL-W2: A Numerical Two-Dimensional, Laterally Averaged Model of Hydrodynamics and Water Quality; User's Manual" (Environmental and Hydraulics Laboratories 1986).

77. Algal and detrital boundary conditions were not known. The algal and detrital flow boundary conditions were each set equal to 0.5 g dry weight/m^3; the detrital head boundary concentration was set equal to 0.5 g/m^3. For comparison, Thomann and Fitzpatrick (1982) used a phytoplankton concentration of 0.7 g carbon/ m^3 (1.6 g dry weight/m^3) at the upstream boundary (Cain Bridge) and 0.5 g carbon/m^3 (1.1 g dry weight/m^3) at the downstream boundary (Chesapeake Bay) of their Potomac estuary application.

78. The sensitivity analysis consisted of a factorial experiment conducted at three levels of algal boundary concentrations (1.25, 2.5, and 5.0 g/m^3) and three levels of algal maximum growth rate (0.25, 0.5, and 1.0 ε/day). The response variable was defined as the tidally averaged algal concentration (see Table 15).

Table 15

Relationship of Tidally Averaged Algal Concentration to Head Boundary Algal Profile Concentration and Algal Maximum Growth Rate

Algal Head Boundary Concentration, g/m^3	Maximum Algal Growth Rate, 1/day	Tidally Averaged Algal Concentration, g/m^3
1.25	0.25	2.8
	0.5	3.0
	1.0	3.6
2.5	0.25	4.4
	0.5	4.7
	1.0	5.4
5.0	0.25	7.7
	0.5	8.1
	1.0	9.2

79. Examination of the results tabulated in Table 15 reveals no interaction between head boundary algal concentration and algal maximum growth rate. Tidally averaged algal concentration was linearly related to both head boundary concentration and maximum algal growth rate. A 100 percent error in estimation of algal head concentration would result in an average algal mass error of 65 percent, whereas a 100 percent error in estimation of maximum algal growth rate would result in an average algal mass error of 11 percent. Light limitation consistently was the factor predicted to limit algal growth.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

General

80. The 2-D laterally averaged water quality code CE-QUAL-W2 characterized the observed longitudinal and vertical gradients of the Savannah River Estuary.

Water quality data resources

81. The data base was adequate for model calibration of the DO-BOD formulation but inadequate for model confirmation. A second, independent data set for model confirmation did not exist.

82. The absence of algal, detrital (or particulate, nonliving, organic matter), and inorganic phosphorus data precluded valid simulation of the algae-nutrient-dissolved oxygen formulation.

83. The application provided the following general comments concerning the existing water quality data base:

a. The center-line survey, consisting of 16 center-line stations sampled on four dates, provided the data used for vertical profile comparisons. The number of center-line stations on the main channel (Savannah River, Front River, and North Channel) was more than adequate. The sampling effort could have been more effectively distributed with six center-line main channel stations extending from Ebenezer Landing downestuary to the mouth of the Savannah River at Fort Pulaski and two center-line stations on the Back River. One center-line site above RM 25 would be adequate.

b. The four sediment oxygen demand study sites were limited in spatial extent. The study sites need to be extended to correspond with the center-line stations on the Savannah River, Front River, Back River, and the North Channel.

Geometric schematization

84. Acquisition of cross-sectional information was a critical problem. Navigation and nautical charts infrequently recorded bottom elevations. The specification of segment widths at elevations no higher than MLW is duplicated by the computer code GEDA at higher elevations. This results in an underestimate of cross-sectional areas during the tidal cycle at surface elevations greater than MLW. Topographic maps did not provide the resolution required.

85. Extensive areas of the Savannah River Estuary are subject to overbank flooding during the tidal cycle. The depth and extent of overbank

flooding can be only tangentially inferred from the nautical charts based on shading representing vegetational cover.

86. Instantaneous water surface elevations extending over several layers resulted in numerical instabilities. Therefore, a surface layer thickness of 5 m was selected with remaining layers 1 m thick.

Tide gate characterization

87. Tide gate operation was successfully simulated by defining Back River as two branches: one upestuary and one downestuary of the tide gate. Flow through the open tide gate was modeled as a submerged weir.

Constituent reactions

88. The existing generality of the water quality constituent formulations in CE-QUAL-W2 permits user latitude in selecting constitutents to simulate and in specifying their interactions. The generality was reflected in the concurrent simulation of BOD and BOD* (Fe_2SO_4).

Boundary conditions

89. The diel study conducted at Ebenezer Landing that was used to specify temperature, DO, and salinity at the upstream flow boundary revealed little diurnal variation. All data collected were used for boundary specification, but diurnal variations were not important and need not have been collected.

90. The 13-hr surveys conducted at the downstream boundary provided adequate data for characterizing intra- and intertidal variation of temperature, salinity, and DO. Examination of time plots of BOD, NH_4, and P revealed that the boundary constituent values could have been averaged for each date and linearly interpolated between dates.

Initial conditions

91. Extended simulation of salinity starting with a concentration of 0.0 ppt revealed that equilibration was achieved in 10 to 20 tidal cycles. The exercise revealed that "hot starts" following simulations extending for greater than 20 tidal cycles were adequate for the specification of initial conditions.

Model adjustment

92. Errors in model geometry manifested themselves as tidal phase and water velocity errors. It is hypothesized that inclusion of overbank flooding would substantially eliminate the phase and tidal errors; adjustment of the Chezy coefficient had little effect.

93. Discrepancies between simulated and measured salinity may be due to errors in advective transport. The simulated surface velocities were less than measured, and adjustment of the horizontal dispersion coefficient had no effect on simulated salinity concentrations.

94. Simulated and measured profiles of temperature, BOD, and DO were nearly equivalent. The results were quite good considering the difficulty in specifying the head boundary conditions and matching the advective transport.

Experimental results

95. Experiments that were conducted demonstrated the utility of CE-QUAL-W2 for investigating changes in upstream regulation and evaluating permit applications.

96. Two sensitivity experiments were conducted in order to evaluate the effects of imprecise specification of head boundary concentrations. The first consisted of a factorial arrangement of DO and BOD head boundary concentrations using simulated tidally averaged DO concentration as the response variable. The results indicated that increasing the head boundary BOD concentration 100 percent decreased the tidally averaged DO concentration 1 percent; decreasing the head boundary DO concentration 50 percent decreased the tidally averaged DO concentration 10 percent.

97. The second sensitivity experiment compared the relative importance of the head boundary algal concentration with the algal maximum growth rate. A 100 percent error in estimation of algal head concentration would result in an average algal mass error of 65 percent, whereas a 100 percent error in estimation of maximum algal growth rate would result in an average algal mass error of 11 percent.

Recommendations

98. Detailed cross-sectional profiles of the study area need to be obtained. The cross-sectional profiles should include areas that are tidally inundated.

99. Specification of external head boundary profiles was critical. The external head boundary profiles may be more easily specified at the mouth of the estuary, where vertical homogeneity can frequently be assumed.

100. The upestuary flow boundary should be specified above the fall line in order to avoid tidal interaction.

101. As a starting point, it is recommended that the following water quality constituents be sampled:

a. Inorganic suspended solids.

b. Salinity.

c. Dissolved organic matter.

d. Particulate, nonliving, organic matter.

e. Algae.

f. Inorganic phosphorus.

g. Ammonia nitrogen.

h. Nitrite plus nitrate nitrogen.

i. Temperature.

j. Dissolved oxygen.

k. Sediment oxygen demand.

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